NATIONAL ACADEMY OF SCIENCES

WALTER HOUSER BRATTAIN

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A Biographical Memoir by

JOHN BARDEEN

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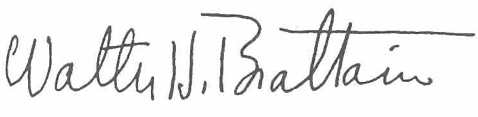

WALTER HOUSER BRATTAIN

February 10, 1902–October 13, 1987

BY JOHN BARDEEN

MOST NOTED AS A coinventor of the transistor, Walter H. Brattain, an experimental physicist, spent the bulk of his professional career at the Bell Telephone Laboratories, first on West Street in New York City and later in Murray Hill, New Jersey. For the discovery of the transistor effect, he shared the 1956 Nobel Prize for physics with William B. Shockley and me. His main interests focused on the electrical properties of surfaces and interfaces, first on thermionic cathodes for applications to vacuum tubes and later on semiconductors for applications to diodes and transistors. Toward the end of his career, he became interested in biophysical problems in which electrolytic conduction plays an important role. Brattain was an initial member of the Bell Solid State Department, formed at the end of World War II to exploit the understanding of properties of solids made possible by quantum theory.

For some years before his retirement from Bell, Brattain taught on a part-time basis at his alma mater, Whitman College, and returned there to teach following his retirement. His research at Whitman was mainly on flow of ions through lipid bilayers in collaborations at Whitman and Battelle Northwest Laboratories.

Brattain loved the Northwest, where he had spent his boyhood. He enjoyed the outdoor life, fishing and hunting, and, as he has said, the more rugged the conditions the better. In autobiographical notes written in 1975, he described his background and early education:

I was born on February 10, 1902, in Amoy, China, where my father was a teacher in the Ting-Wen Institute for Chinese boys. My parents returned to their native state of Washington in 1903, and that part of my childhood that I can remember was spent in Washington, first in Spokane until I was nine years old and then on a homestead near Tonasket.

My parents, Ross R. and Ottilie Houser Brattain, were both born in the territory of Washington of pioneer stock. My father was born near Farmington and my mother in Colville where she was baptized by Cushing Eells who founded Whitman College in honor of his fellow missionary Marcus Whitman.

My father graduated from Whitman College in 1901. He was first a teacher in Amoy, China, then a stockbroker in Spokane, then a homesteader, cattle rancher and flour miller in Tonasket. His father, William Cullen Brattain, crossed the plains from Iowa to Springfield, Oregon, in 1852, as a boy 16 years old with his father Paul Brattain whose Quaker grandparents Robert Brattain and Mary (Millican) Brattain were born in Randolph County, North Carolina, 1746 and 1747. My grandfather did some prospecting for gold but spent his life farming. My grandmother, Agnes McCalley Brattain, was born in the Canadian Province of New Brunswick and crossed the plains to Springfield, Oregon, from Chicago in 1859 when she was four years old with her father Andrew McCalley and mother, Christine (Millar) McCalley, both from Scotland.

My mother went first to Whitman College and then to Mills College, California, where she graduated in 1901. Her father, John Houser, came to the West across the plains to San Francisco in 1854 from Stuttgart, Germany. Her mother Marie (Reiniger) Houser, also from Stuttgart, came over later. My grandfather finally settled in Pomeroy, Washington, where he had his own flour mill which still is standing today.

From my ninth year on, the chief family occupations were farming, cattle ranching and flour milling. I rode after cattle in the mountains and carried a rifle when I was 14, and during school vacation I worked alongside my father from this age on.

I first went to Roosevelt grade school in Spokane, then rode horseback five miles to Tonasket to go to grade school. I was promoted a grade because of my ability with arithmetic. High school: Queen Anne, Seattle, first year; Tonasket High School, second and third; Moran School, Bainbridge Island, fourth year. Stayed out of school and worked on our cattle ranch for one year between my junior and senior years of high school.

Brattain had a younger brother, R. Robert ("Bob"), also a physicist, who had an outstanding career with the Shell Oil Company, and a sister, Mari, both of whom survived him.

With financial help from an aunt, Walter followed his parents and attended Whitman College. He was stimulated to study physics by an outstanding teacher, Benjamin H. Brown, who had many students who went on to successful careers. His parents had also taken courses under Professor Brown. The physics majors in 1924 in addition to Brattain were Walker Bleakney (professor at Princeton), Vladimir Rojansky (professor at Union and Harvey Mudd colleges), and E. John Workman (president, New Mexico School of Mines), all of whom had distinguished careers. The members of this famous class were known as the "four horsemen of physics."

Bleakney tells an anecdote about Brattain's student days that illustrates the determination in response to a challenge that he showed in later years:

Once he asked Professor Brown about a problem, the nature of which I can no longer recall, and Brown said we could not solve it because we had not yet studied the necessary tools. But Walter persisted, and Brown said to him, "If you solve it, I will excuse you from the final exam and give you a grade of 90." Of course Walter rose to the challenge and in a few days he did achieve the solution. Brown sheepishly admitted he had made a mistake but lived up to his promise. When the other three of us were slaving over the final exam Walter was gleefully chortling on the sideline. But we had the last laugh. When the final grades came out Walter's was the lowest in the class! You can be sure we did not let him forget that.

Following Whitman, Brattain attended the University of Oregon, where he received an M.S. in physics. He then went on to the University of Minnesota to do a Ph.D. thesis under John T. Tate on "Efficiency of Excitation by Electron Impact and Anomalous Scattering in Mercury Vapor." He left in the fall of 1928 to take a position at the U.S. National Bureau of Standards, where he spent a year before joining Bell Labs.

When Brattain was a graduate student, the revolution in understanding at the atomic level brought about by quantum theory was under way in Europe. Few physicists in the United States were knowledgeable about quantum theory. In the late twenties, many young American scientists went to Europe to learn about the exciting developments taking place. Brattain was fortunate to be able to study quantum mechanics at Minnesota under John H. Van Vleck, then a young Harvard Ph.D. who was a pioneer in applications of quantum concepts to solids. His course in quantum theory must have been one of the first given in this country. Brattain often mentioned that he was fortunate to be in graduate school at the beginning of the period when scientists no longer *had* to go to Europe to study quantum physics. Another professor Brattain credits with being an important influence was Joseph Valasek, whose interest was in piezoelectricity.

At the Bureau of Standards, Brattain worked in the Radio Division, where he was mainly interested in the development of piezoelectric frequency standards. In 1929 he met Joseph A. Becker, a staff member of Bell Laboratories, at a meeting of the American Physical Society. Becker took a liking to him. It did not take much persuasion to get Brattain to transfer to Bell, the premier industrial laboratory in the country. For more than a decade, Brattain worked closely with Becker on a variety of problems on thermionic emission and on copper oxide rectifiers.

I first met Walter in 1934 through his brother, Bob, who at that time was a fellow graduate student with me at Princeton. Walter and I had a common interest, since my Ph.D. thesis, under the direction of E. P. Wigner, was on the theory of the work function as derived from the quantum theory of metals. Brattain was then living alone in an apartment in Greenwich Village in New York City and working at the West Street laboratories of Bell.

In the spring of 1935, Brattain married Karen Gilmore. A native of Ohio, Karen received a Ph.D. in physical chemistry from the University of Minnesota. It proved to be a good match, her calm demeanor serving as an antidote to Walter's somewhat volatile temperament. They had one son, William, born in 1943. Unfortunately, Karen died prematurely of cancer in 1957, but lived long enough to accompany Walter to the Nobel ceremonies in Stockholm in December 1956.

In the depression days of the 1930s, Bell had a hiring freeze. No new staff members were added between 1930 and 1936. During much of this time, they worked short hours at reduced pay. Many took advantage of the extra free time to take courses at Columbia or to participate in informal study groups at Bell. There was much interest in learning more about the quantum theory of solids. One of the first hired after the freeze was lifted was William Shockley, a Ph.D. student of John Slater at MIT. He and Foster Nix organized a study group in solid state physics, in which Brattain was an active participant.

Interest in quantum mechanics at Bell was stimulated by the Nobel Prize-winning experiments of C. J. Davisson and L. H. Germer, which showed that electrons have wave properties, as had been suggested by de Broglie and by Schrödinger. Arnold Sommerfeld had given a simplified model of a metal in which it was assumed that the outer electrons become detached from the metal atoms to form a sea of electrons obeying Fermi-Dirac statistics. The sea of electrons moves in a positive background formed from the metal ions.

Sommerfeld's theory provided a microscopic model from which one could calculate the temperature dependence of thermionic emission in terms of the work function, the energy required to take an electron from the uppermost occupied energy levels of the metal and place it outside one of the crystal faces of the metal. Although Bell Labs did not have any theoretical physicists working on quantum theory, Karl Darrow wrote a series of semipopular articles, many published in the *Bell System Technical Journal,* that helped make the quantum ideas more widely known. One of the first of these articles, published in 1929 in the first issue of *Reviews of Modern Physics,* described Sommerfeld's theory of metals. Sommerfeld made a world tour in 1931 in which he helped spread his ideas. One of his stops was at a summer school at the University of Michigan. Among those attending the lectures was Walter Brattain. He and Becker later did a series of experiments on thermionic emission that helped to give experimental verification of the Sommerfeld theory.

These experiments involved techniques that Brattain used later in experiments that led to the discovery of the transistor effect. Thermionic emissions and emission under the influence of an electric field (field emission) depend on the work function of the surface. Differences in work function between two surfaces are equal to the contact potential difference, the difference in potential outside the two surfaces when there is an electric contact between the two metals. Brattain and Becker found that the difference in work functions as determined from thermionic emission is equal to the difference in contact potentials.

Other experiments they did involved studies of effects of adsorbed atoms on the work function of tungsten. Atoms that are adsorbed as positive ions tend to decrease the work function and increase the thermionic emission. Brattain and Becker studied the effect of adsorbed thorium as a function of surface coverage and found that the work function is a minimum when the surface is completely covered with one adsorbed layer.

The other major problem that Brattain and Becket worked on during prewar years was to try to understand rectification at the interface between copper and its oxide Cu_2O. The rectification was discovered by L. O. Grondahl and P. H. Geiger in 1927, who found that the ratio of the current between forward and reverse directions could be as large as 4,000. Copper oxide rectifiers were used in the telephone system primarily as a modulator in carrier systems. Making the rectifiers was largely an empirical art—copper was oxidized by heating in air, and an electrode (e.g., aquadag) was painted on the outer surface of the oxide. It was not until the late thirties that an adequate theory of rectification was given by Nevill Mott and Walter Schottky.

One of the last research projects undertaken by Brattain before the war was an investigation of the rate of oxidation of copper at different temperatures using a radioactive copper tracer. He was also a participant in some of the early work on silicon for application to cat's whisker detectors for radar. Since vacuum tubes did not operate at the high frequencies involved, resort was made to the point-contact semiconductor detectors of the early days of radio. The further development of silicon and germanium for radar during the war by the MIT Radiation Laboratory, the University of Pennsylvania, and Purdue University provided essential background for the discovery of the transistor.

Brattain and his family moved to New Jersey when Bell opened up the Murray Hill Laboratories. During the war many of the staff members were involved with military problems unrelated to their peacetime research interests. Brattain spent two years working on airborne magnetometers for detection of submarines.

In the summer of 1945, as the war was drawing to a close, plans were formulated by Mervin Kelly (then executive vice-president) and others for an interdisciplinary solid state department. The hope was to apply the understanding of solids at the atomic level made possible by quantum theory to develop new materials for components in the telephone system.

The Solid State Division, with Shockley and Stanley O. Morgan as coheads, was an interdisciplinary one consisting of chemists and physicists as well as engineers familiar with the problems of telephone communications. Also included were theorists who had begun to develop an understanding of the properties of solids from the atomic point of view. While most members were long-time Bell employees, most of the theorists were recruited from outside. I joined the division in the fall of 1945, after World War II came to a close.

The initial semiconductor group, one of several in the division, consisted of Walter Brattain and Gerald Pearson, experimental physicists; Robert Gibney, a physical chemist; and Hilbert Moore, an electrical engineer. Initially, because of wartime crowding, I shared an office with Brattain and Pearson and became interested in semiconductors.

A long-term goal was to make an amplifying device with a semiconductor to replace the vacuum tube. The result was the transistor, essentially an electrical valve with three electrodes such that a voltage applied to one can be used to control the current flowing between the other two. There had been considerable development of germanium and silicon as diodes for use as detectors for radar during the war. Being elements, they were easier to purify and their properties easier to understand than those of compound semiconductors. We decided to concentrate our efforts on these materials, then available in the form of reasonably pure polycrystalline ingots. Shockley had suggested what is now known as a thin-film field-effect transistor, but initial attempts to make such a device had failed.

None of us had worked on semiconductors during the war, so we were eager to learn about the developments that had taken place. With new materials to study and new concepts to help understanding, it was a very exciting time to be involved in semiconductor research. We followed the Bell Labs tradition of forming study groups to learn about what had been accomplished.

Those involved with the research were good friends socially as well as scientific collaborators. The Brattains were active members of a duplicate bridge club. Walter and I were partners in bridge games arranged at Bell Labs. We were also enthusiastic golfers and enjoyed many a match together. When we lived in different places we would try to get in a round of golf when we got together at scientific conferences in this country and abroad.

In an interview given in later years, Brattain recalls:

> I cannot overemphasize the rapport of this group. We would meet together to discuss important steps almost on the moment of an afternoon. We would discuss things freely, one person's remarks suggesting an idea to another. We went to the heart of many things during the existence of this group and always when we got to the place where something had to be done, experimental or theoretical, there was never any question as to who was the appropriate man in the group to do it.

The close collaboration between experimentalists and theorists extended through all stages of the research, from the conception of the experiment to the analysis of the results. Most papers were authored jointly by an experimentalist and a theorist. Brattain concentrated on surface and interface phenomena, while Pearson concentrated on current flow in the bulk of a semiconductor.

Early in our studies we learned about the theories of rectification at a contact between a metal and a semiconductor that had been developed by Mott and Schottky. The more complete theories of Schottky and his co-worker E. Spenke, done early in the war, were not available in the West until after the war.

Current in a semiconductor can be carried in two different ways, by conduction electrons, extra electrons that do not fit into the valence bonds, and by holes, places where electrons are missing from the valence bonds. The first is called n-type, from the negative charge of an electron, and the second, p-type. Silicon and germanium are ambipolar; they can be either n-type or p-type, depending on the nature of the impurities present. By thermal excitation or by light (photoconductivity), electrons can be excited from the valence bonds, giving equal numbers of conduction electrons and holes to add to the conductivity. What we discovered in the course of research is that the conductivity can likewise be enhanced by current flow from an appropriate contact, the principle of the bipolar transistor. Both the field-effect and bipolar principles are used in present-day transistors and integrated circuits.

The experiments that led to the discovery of the bipolar principle and to the invention of the point-contact transistor were done in December 1947. The point-contact transistor consists of two metal (cat's whisker) contacts on the upper surface of a small block of germanium that had a large-area, low-resistance contact on the base. Each point contact by itself forms a rectifying contact relative to the base. One, the emitter, is biased in the direction of easy flow; the other, the collector, is biased to a higher voltage in the reverse direction. A signal applied between emitter and base appears in amplified form between collector and base.

Within less than a month, Shockley suggested the junction transistor in which the entire action takes place within the bulk of a semiconductor rather than at metal-semiconductor contacts. All present-day bipolar transistors are of the junction type. Both field-effect and junction transistors put much greater demands on control of material properties than point-contact transistors. It took almost two years before the first junction transistors were made in the laboratory and several more years before they were put in production. It took more than a decade for materials technology to reach the stage required for field-effect transistors.

An essential step was the growth of large, highly pure single crystals, initiated by Gordon Teal in 1948. It was also necessary to learn how to introduce foreign elements to control the conductivity (n- or p-type) in minute regions of the crystal. The introduction of integrated circuits did not occur until the early 1960s, nearly fifteen years after the initial invention.

The first transistor to be put in production by Bell Labs was the point-contact transistor in a form designed in large part by William G. Pfann in 1948. It was produced and used in the Bell system for approximately a decade. Another early form was the alloy transistor in which alloy junctions are made on opposite faces of a thin slab of germanium.

While the point-contact transistor was relatively easy to make, its operation was difficult to understand in detail. Brattain undertook a series of experiments to help understand how minority carriers (holes in n-type germanium) flow from the emitter point and how minority carriers introduced flow to and add to the collector current. The collector point was formed by passing a large current through it so as to alter the characteristics of the germanium in the vicinity in an unknown way. Immediately adjacent to the surface of the germanium there is a thin layer (inversion layer) of p-type conductivity with the charge of the added holes balanced by electrons in bound states at the surface of the germanium. It was learned soon that holes introduced at the emitter could flow in and add to the conductivity of the n-type bulk, as in a junction transistor. These experiments led to a better understanding of how the current-voltage characteristics of the point-contact transistor depend on the parameters involved.

Also important was learning how an inversion layer of opposite conducting type is formed at the free surface of a semiconductor with the charges balanced by electrons in surface states. I collaborated with Brattain in this study for a couple of years after I left Bell to go to the University of Illinois in 1951, and he later worked with C. G. B. Garrett and with P. J. Boddy. He showed that the inversion layer could be varied considerably by surface ambient. This work was important for junction devices where one wants to passivate the surface so as to avoid a harmful inversion layer.

Some of the experiments with Boddy were to study effects of electrolytes adjacent to a semiconductor surface. Brattain became interested in blood clotting when his son, Bill, underwent heart surgery. This led to an interest in electrochemical processes in living matter. Several papers were written in collaboration with Boddy and P. N. Sawyer on vascular prostheses and related problems. He continued these interests after moving to Whitman College, where he collaborated with David R. Frasco of the Chemistry Department at Whitman and with Donald R. Kalkwarf of Battelle Institute at Richmond, Washington. Some of this work involved flow of potassium ions through lipid bylayers, in which he saw some analogies with flow of electrons through metal-semiconductor rectifying junctions.

Brattain was for many years an active participant in international meetings conducted by the Commission on Semiconductors of the International Union of Pure and Applied Physics. He served on the commission for several years and was the chairman in 1966. As long as he was able, he was a regular attendant at meetings of the National Academy of Sciences. He took great pleasure in attending meetings of Nobel laureates and students at Lindau, West Germany, organized by Count Bernadotte, a descendant of the Swedish royal family. Through his membership on the Defense Science Board, he became a good friend of Senator Henry ("Scoop") Jackson.

Brattain's years at Whitman College were certainly among the happiest of his life. He enjoyed teaching undergraduates. A favorite course was "Physics for Nonscience Majors," one taught earlier by Professor Brown. His marriage to Emma Jane (Kirsch) Miller in May 1958 was a happy one. They both enjoyed travel and music. He played golf regularly at the local country club, and he resumed fishing in rugged surroundings.

A victim of Alzheimer's disease, he spent the last four and a half years of his life at a nursing home in Seattle, where he died on October 13, 1987. Pearson, who had a distinguished career at Stanford following his retirement from Bell, survived Brattain by less than two weeks.

Brattain was elected to the National Academy of Sciences in 1959. In addition to the Nobel Prize, he received the Stuart Ballantine Medal and the John Scott Medal. He was an honorary member of the Swedish Royal Society and of the Institute of Electrical and Electronic Engineers and a fellow of the American Physical Society and of the American Academy of Arts and Sciences. He was a recipient of six honorary degrees, including those from his three alma maters. He was elected to the National Inventors Hall of Fame and posthumously to the Information Processing Hall of Fame of INFOMART.

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