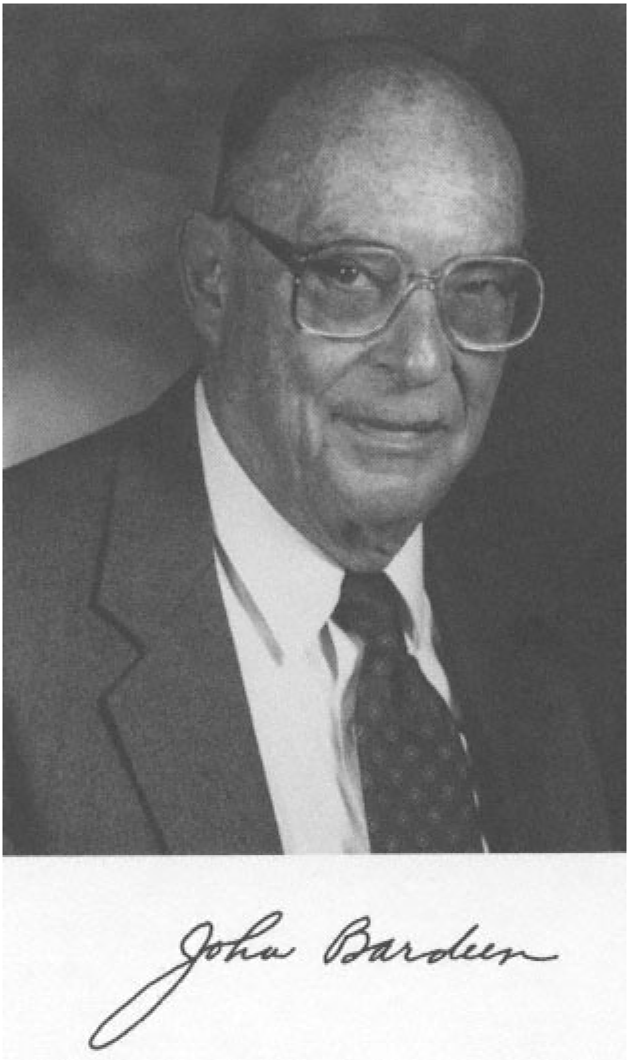

John Bardeen

1908-1991

By Nick Holonyak, Jr.

IN JOHN BARDEEN'S own words:

In any field there are golden ages during which advances are made at a rapid pace. In solid-state physics, three stand out. One, the early years of the present century, followed the discoveries of x rays, the electron, Planck's quantum of energy, and the nuclear atom—the discoveries that ushered in the atomic era. The Drude-Lorentz electron theory of metals and Einstein's applications of the quantum principle to lattice vibrations in solids and to the photoelectric effect date from this period. Von Laue's suggestion in 1912 that a crystal lattice should act as a diffraction grating for x rays and research of the W. H. and W. L. Bragg [sic] opened up the vast field of x-ray structure determination.

The foundations of the field were firmly established during a second very active period, from about 1928 until the mid-thirties, which followed the discovery of quantum mechanics. Many of the world's leading theorists were involved in this effort. The Bloch theory, based on the one-electron model, introduced the concept of energy bands and showed why solids, depending on the electronic structure, may be metals, insulators, or semiconductors. The fundamentals of the theory of transport of electricity and of heat in solids were established. In these same years, the importance for many crystal properties of the role of imperfections in the crystal lattice, such as vacant lattice sites, dislocations, and impurity atoms was beginning to be recognized. Some of the names prominent in the developments of solid-state theory during this period are Bloch, Brillouin, Frenkel, Landau, Mott, Peierls, Schottky, Seitz, Slater, A.

> H. Wilson, Wigner, and Van Vleck. The third golden age has been the rapid expansion in the post-World War II years, with not only great advances in understanding but also in technology and new products. (*Physics 50 Years Later* Washington, D.C.: National Academy of Sciences, 1973, pp. 166-167.)

If we look for a specific date for the beginning of the "third golden age" of solid-state physics, the logical choice is when Bardeen identified carrier injection in a semiconductor, that is, when Bardeen and Walter Brattain first demonstrated (December 16, 1947) the transistor and with it a new principle for an amplifying device (*Physical Review* 74 [1948]: 230; U.S. Patent 2,524,035, filed June 17, 1948). Who would have believed that the Ge band structure, which was then unknown, and carrier lifetime would have permitted carrier injection, collection, and signal amplification, even if the idea, the notion of a transistor, existed? The semiconductor suddenly took on new importance, and a revolution in electronics followed. With John Bardeen's death on January 30, 1991, we have passed to another era, maybe now more evolutionary than revolutionary.

John Bardeen was born May 23, 1908, in Madison, Wisconsin, where his father, Dr. Charles R. Bardeen, was dean of the University of Wisconsin medical school. His mother, Althea Harmer Bardeen, was trained as an interior decorator and died in Bardeen's youth, his father later remarrying. Except for his Ph.D., all of John Bardeen's formal education occurred in Wisconsin. He was a true prodigy and at nine years of age skipped from third grade to seventh grade. It is interesting that many years later when he occasionally misspelled a word he attributed this to the drill in spelling he missed in skipping many grades of elementary school. In spite of his obvious talent for mathematics and science, he was given to normal play, mischief, and friendship with his contemporaries, and exhibited a fondness for various sports. He learned golf very early and played the game at a high competitive level all of his life, even into his eighties when his eyesight was failing. Maybe his interest in golf equaled or exceeded his other interests. He had a good sense of humor and admitted that maybe two Nobel Prizes (physics, 1956 and 1972) were better than the hole-in-one he once made. At the University of Wisconsin he was on the swimming team and also played billiards. One of his wartime coworkers at the Naval Ordnance Laboratory (1941-1945) commented many years later that Bardeen was also not to be challenged in bowling. In addition, he apparently was good at cards and was able in his youth to earn spending money playing poker.

After finishing high school at age fifteen, Bardeen entered the University of Wisconsin and, in spite of his interest and ability in mathematics and physics, studied electrical engineering, receiving a B.S. in 1928 and an M.S. in 1929. This is one of the first indications of another side of Bardeen, his considerable appreciation for the practical as well as his ability to invent. It was not possible for him, however, to suppress his talent and interest in mathematics and physics, and at the University of Wisconsin in his first year as a graduate student (1928) he learned quantum mechanics from Van Vleck and later from Dirac, who delivered lectures in Madison based on the famous book published a year later. Instead of finishing his graduate education, Bardeen followed a University of Wisconsin professor to Pittsburgh to work (1930-1933) for Gulf Research and Development Corporation on problems dealing with oil exploration. He became a successful geophysicist, with some of his ideas in oil exploration still kept confidential. Besides his work at Gulf, his golf, and attending seminars on quantum physics at the University of Pittsburgh, he became acquainted with Jane Maxwell, whom he later married (1938), and with whom he raised a family and spent his entire life.

In spite of his success working on geophysical problems, John Bardeen quit his steady employment with Gulf in the heart of the Great Depression to go to graduate school at Princeton University (1933-1935). He had heard that Einstein was coming to Princeton and thought there might be a possibility of working with him. As it turned out, Einstein did not take graduate students, and Bardeen wound up in the Princeton mathematics department (not physics) working for Eugene Wigner, one of the two brilliant young Hungarians (the other was John von Neumann) who had recently arrived in America. Frederick Seitz was Wigner's first research student, Bardeen the second, and

Conyers Herring the third, which was sufficient to identify Princeton as a center of solid-state physics. For his thesis dealing with the calculation of the work function of metals, Bardeen was awarded his Ph.D. in mathematical physics in 1936.

Before his Ph.D. was completed and through the influence of Van Vleck, who had moved from Wisconsin to Harvard University, John Bardeen took a position (1935-1938) as a junior fellow of the Society of Fellows at Harvard, where, incidentally, he overlapped with, among others, James B. Fisk (later of Bell Labs) and Stanislaw Ulam. This was the first time Bardeen was actually in a physics department. At Harvard he worked with Van Vleck and Percy Bridgman, the great high-pressure scientist, and in Cambridge interacted with John Slater and his students at the Massachusetts Institute of Technology. Slater later forgot and referred to John Bardeen as his post-doc. It was Bardeen's Princeton and Harvard years that laid the foundation for his future work. For example, in one of his Urbana seminars in 1970, he mentioned that already at Harvard he had the notion that superconductors possessed an energy gap. Before he became involved in semiconductor research in 1945, he was already deep into the study of metals and superconductors, but had not necessarily decided to pursue solid-state theory as a career.

After Harvard, John Bardeen took a teaching position (assistant professor, 1938-1941) at the University of Minnesota, ironically for a salary much less than he received at Gulf. Before World War II actually began, he went on leave to the Naval Ordnance Laboratory (1941-1945) and worked on problems of ship degaussing and underwater ordnance. At the war's end, and with the need for increased salary for a growing family, he joined the newly formed Bell Telephone Laboratories group that set about acquiring a more fundamental understanding of solids (semiconductors) and launched, at Kelly's urging, the search for a solid-state replacement for the vacuum tube. Because space was short, Bardeen, a theorist, wound up sharing an office with Walter Brattain and Gerald Pearson, experimentalists, and thus began an intensive collaboration of historic consequences.

At Bell Labs Bardeen first checked existing calculations on the operation of a field effect device (an old idea), and agreed the calculations were correct and that the failure of the device was not one of principle. Bardeen made the important suggestion that surface states on Si or Ge, the preferred experimental materials (a consequence of World War II developments), immobilized the carriers and thwarted conduction and field effect amplification. We cannot describe here all of Bardeen's published work, several hundred papers, but wish to mention his famous 1947 paper (*Physical Review* 71 [1947]: 717) on surface states, which, among other features, reveals how thoroughly Bardeen understood the symmetry in electron and hole behavior, that is, the importance of both. This proved later to be of some consequence in permitting recognition of carrier injection. The problem with surface states led to an intensive study of surface effects with Walter Brattain. Bardeen realized that fundamental problems existed with evaporated films then used in field effect experiments, and suggested instead, as a thin conducting channel, the use of inversion layers on bulk crystals of known good properties. The first working field effect device, at first on Si and then Ge, employed Bardeen's inversion layer suggestion. It should be noted that Bardeen's inversion layer idea (U.S. Patent 2,524,033, October 3, 1950, filed February 26, 1948) is the basis for today's CMOS devices, now so critical in integrated circuits. Most individuals are unaware of where this idea originated.

It is a fascinating story to follow how Bardeen and Brattain, by removing the surface electrolyte (a convenient but "slow" mechanism of field modulation) on their field effect device and by substituting a gold field plate on the crystal, realized instead a gold injection electrode (on n-type Ge) and in the process demonstrated an entirely new device. The device, operating on entirely new principles, was the transistor. Several modifications led to the point contact version of the transistor, which was merely an experimental simplification of Bardeen and Brattain's first transistor, the first occurring on December 16, 1947, and a demonstration to the "brass" (Bardeen's word) on December 23, 1947. Not only did Bardeen and Brattain introduce the bipolar transistor—a new idea, a new principle, a new device, a new name—they also introduced a first embodiment, a direct way to convert a crystal into an amplifying or switching device. Bardeen has left an account of all of this work and how it occurred in his June 1990 NHK (Japanese television) interview. The new device demonstrated by Bardeen and Brattain, the transistor, the bipolar device based on carrier injection (which Bardeen identified), served as the prototype for all bipolar and injection devices that followed. A new device principle had been established with carrier injection, and Bardeen and Brattain's transistor and, whether it was realized or not (December 1947), the semiconductor took on then a new level of importance. In fact, semiconductor electronics as known today enjoyed its beginning, and it is proper to say that the "third golden age" of solid-state physics had truly begun.

It was inevitable, since he was in the same office with Brattain and Pearson, that John Bardeen would be drawn into semiconductor work, where indeed, his talents had an immediate and major impact. For various reasons, however, some dealing with Bardeen's broader interests (including superconductivity), some organizational, and some being the opportunities that existed elsewhere, he left Bell Labs in 1951 and came to the University of Illinois (Urbana), where he spent the rest of his life. Illinois was attractive to him because Seitz and others had already established a base in solid-state research and, with a joint appointment in electrical engineering and physics, John Bardeen could expand the solid-state research in Urbana, as he chose, into semiconductor and superconductivity research. In 1951 he began his teaching activities, and in 1952 he founded a semiconductor research activity in electrical engineering and, in physics, began a further push to solve the long mysterious problem of superconductivity.

At Illinois, besides continuing his work on semiconductors and training a new generation of engineers and applied physicists who have themselves made major contributions to semiconductor and solid-state research and its applications to electronics, John Bardeen, with L. N. Cooper and J. R. Schrieffer, constructed (1957) the first successful theory of superconductivity, the so-called pairing theory. This theory, the Bardeen, Cooper, and Schrieffer (BCS) theory, is universally recognized as providing the correct account of the superconductivity of metals, a phenomenon discovered nearly fifty years earlier (1911). From the time of its discovery, superconductivity remained unexplained and was studied by a long list of outstanding physicists, including such great men as Felix Bloch, Niels Bohr, Richard Feynman, Werner Heisenberg, Lev Landau, Fritz London, and Wolfgang Pauli. This gives some idea of the importance attached to this long-unsolved problem and of the genius of John Bardeen in recognizing how to go about attacking it. No one else had a better understanding of the problem and how it might be solved. A solution for the problem of superconductivity ranks as one of the major achievements of physics and technology of this century. Superconductivity, of course, has important practical applications (e.g., high-field magnets) and is perceived as offering even a wider range of important uses now that a new family of so-called high T_c oxide superconductors has been discovered.

The BCS theory is considered the standard for judging and explaining superconductivity in all of its various manifestations, and has provided also the basis for major advances in related fields. It has been used to explain a number of puzzling facts concerning the structure of nuclei. The "pairing" ideas characteristic of the BCS theory play nearly as basic of a role in theories of nuclear structure as they do in the explanation of the superconductivity of metals. BCS ideas have influenced also the theory of elementary particles and superfluid helium.

John Bardeen had a unique influence on the technical and scientific life of our time. As already mentioned, he, with Brattain, identified minority carrier injection in semiconductors and invented the transistor. This event started a revolution in electronics and computer technology that is unparalleled and that continues to grow. No other invention of our time has had such a profound effect on society. John Bardeen had an equally profound influence on contemporary physics with the creation of the BCS theory of superconductivity, and its far-reaching influence on superconductivity itself and on various related problems. Bardeen was regarded as one of the world's great solid-state theorists. He was equally renowned as, and was first, an engineer and inventor. His work shed light on nearly every corner of the field of solid-state physics and the conductivity of solids (metals, semiconductors, superconductors, photoconductors, and linear conductors). The foundation of modern electronics rests on much of John Bardeen's work on the conductivity of solids. Even the light emitters and lasers of present-day optoelectronics rely on the mechanism of carrier injection that begins with Bardeen and Brattain's original bipolar transistor.

John Bardeen spoke in a soft voice and at times could be inaudible, particularly when he was tired, deep in thought, or in a long, involved discussion. Some students dubbed him "silent John" or "whispering John," which was a little unfair considering how generously and fairly Bardeen treated students, and similarly colleagues, coworkers, and everyone in general. Everyone sought his advice. In fact, legend held that he was infallible, which, of course, was untrue, but which, of course, had much substance considering his great talent and success as a scientist and engineer. It was known that he didn't say much, but what he said was carefully thought out and important to hear. He was in heavy demand for advice, talks, seminars, committee service, and university, government, and industrial consulting. For example, it was well known that he had no small part in helping the Xerox Corporation in the development of several aspects of the xerographic process. He always gave the best possible advice, and was never intimidated, not even by presidential committees. John Bardeen was a man of the highest integrity and never allowed his name to be used improperly or falsely.

On difficult doctoral examinations he often was the voice of reason that could see where the candidate had ability and was apt to make a contribution. He always looked for the best in others, not the worst. The standards he set for himself, for example, were not what he imposed on others. It was amusing to see him smile when he received a preprint, sometimes wrong, from someone coming into an area of work Bardeen initiated. Problems he worked on quickly drew others. It is hard to estimate the total number of students, post-docs, visitors, and advisees of all sorts that owed their start to John Bardeen. He was a teacher of the highest order, by example and accomplishment, not by popularity vote. It is also hard to estimate how often he was approached to write letters of recommendation for awards, academy memberships, etc., and the burden that this created. John Bardeen was kind and very generous and gave much of himself to others. It seemed his time was never his own. Nevertheless, he somehow managed to be a productive scientist and engineer even as his health was failing. In fact, over the years his publication rate did not change, in spite of his great fame and all the demands on his time. Only a month before his death he published a paper in *Physics Today* (December 1990) on his most recent thoughts and work. Right up to the end of his life, he regularly gave talks and seminars on the "early days of solid-state and transistor research" as well as on superconductivity. Just before his death, he was sorting and assembling material to prepare an account of the history and development of superconductivity, which perhaps no one knew as did John Bardeen.

John Bardeen was a rarely gifted person (cf., *Physics Today,* April 1992) and, of course, received many honors, including the unprecedented award of two Nobel Prizes in physics. His mathematical and analytical skills were of the highest order, and his intuition for "right and wrong physics" incomparable. He was able to untangle and simplify problems—important, difficult (even messy) problems—that stopped the best minds. With the transistor and BCS theory of superconductivity, not to mention his other work, he left science and technology, and indeed, the world, much richer than he found it. He, more than anyone else, can be said to be the "godfather" of modern electronics. We will always be inspired by him and be in his debt.