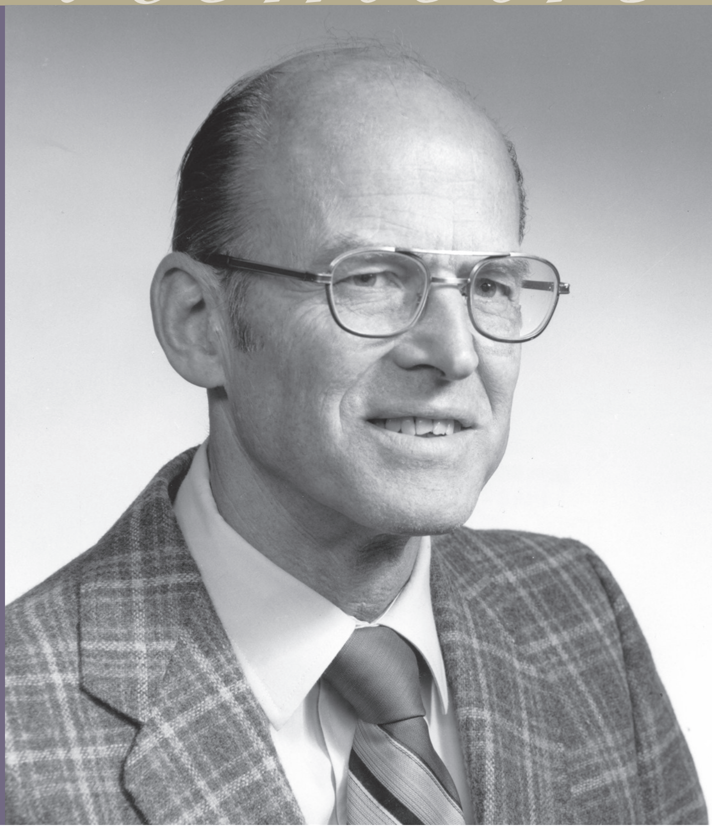
Robert N. Hall

1919–2016

BIOGRAPHICAL *Memoirs*



A Biographical Memoir by
Gerald D. Mahan

NATIONAL ACADEMY OF SCIENCES

ROBERT NOEL **HALL**

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By Gerald D. Mahan

Robert N. Hall, a pioneer in the early days of semiconductor physics, spent almost his entire career at the Research and Development Laboratory of the General Electric Co. in Schenectady, N.Y. Bob was the first scientist to propose the nonradiative recombination of electrons and holes, now called the Shockley-Hall-Read process, and he was the first to patent the two most important methods—alloying and diffusion—for making semiconductor diodes, which made GE an early leader in the manufacture of semiconductor devices. He led a research team that invented the semiconductor injection laser, obtained the patent that device, and authored the first publication about it. He also devised the principal method for making very-high-purity silicon and germanium, and he used these materials to create a device for measuring nuclear radiation.

Born in New Haven, CT, to Harry and Clara Hall, Bob attended the California Institute of Technology, graduating with a B.S. degree in physics in 1942, and he subsequently obtained his Ph.D. in physics from Caltech in 1948. In the midst of his studies, Bob worked for Lockheed Aircraft (1940–1941) and General Electric/Schenectady (1942–1946) as a test engineer. During that period at the GE R&D Laboratory, he helped design and build continuous wave magnetrons to jam enemy radar. His version of the magnetron was subsequently used to operate most microwave ovens.

Upon receiving his Ph.D., Bob accepted a position back at the GE Schenectady lab, in its semiconductor division, where one of his earliest projects involved transistors and power rectifiers using germanium. This work led to developments in AC-to-DC power conversion, which is the basis for charging all portable electronic devices such as cell phones and laptop computers. In those early days of semiconductor technology, germanium was the preferred material. Meanwhile, the Bell Laboratory team of John

Robert Hall, Dora Hall, father Harry Hall, Richard Hall, son. California, summer of 1948.

Bardeen, Walter Brattain, and William Shockley invented the germanium transistor. But when a farsighted GE manager named Leroy Apker suggested that silicon would be a better semiconductor, Bob began working on silicon devices. The short-term result was that GE became the leading manufacturing company in those early days, when transistor devices were placed on pegboard circuits. The long-term result is that today virtually all computers, cell phones, and similar devices use silicon technology.

Pure silicon and germanium, which are insulators, become useful electronic components when "impurities—atoms of other elements—are added to them; these impurities enable silicon and germanium to conduct electricity. The Bell Laboratory team had made transistors by means of ion implantation, which uses an ion accelerator, to inject the impurities. But Bob quickly invented and patented two easier ways of adding impurities to make transistors: alloying; and impurity diffusion from the surface. These two methods became the basis of all transistor manufacturing, GE became the world's largest producer, and Bob became the leading semiconductor physicist at GE—a role he maintained throughout his career.

In 1958, after Leo Esaki reported the first electron-tunneling experiment in a p-n junction of gallium arsenide (GaAs), Bob began studying electron tunneling too. In 1960, he discovered in GaAs new phenomena that are now called "zero-bias anomalies," when there is a very large and narrow peak in electrical conductance as the voltage nears zero. Previous measurements had been of the electrical current I as a function of the voltage V across the semiconductor diode. Bob got the idea of adding a small oscillating voltage of amplitude v and frequency ω, such that V(t) = V + v*cos (ωt). Then he measured the part of the current that oscillated with the frequency, which was in fact the electrical conductance dI/dV. This phase-sensitive measurement is now a standard practice around the world, but Bob and his colleague Jerry Tiemann, another GE physicist, were the first people to do it. Before long, researchers around the world started doing phase-sensitive measurements, and zero-bias anomalies were discovered in many other systems. Later work by GE theorists showed that the zero-bias anomaly in GaAs was caused by atom vibrations called phonons.

Richard Hall, Dora Hall, Robert Hall, Elaine Hall. December 1963.

In 1962, Bob's GE team of Gunther Fenner, Jack Kingsley, Ted Soltys, and Bob Carlson was vying with its counterparts at other companies' laboratories to develop a semiconductor laser, which ultimately became by far the most useful laser ever invented. The GE team was the first to succeed, and the researchers quickly wrote up their results and sent the manuscript to *Physical Review Letters*, a leading journal in the field. Following standard procedure, the *PRL*'s editors then sent the manuscript out to review. But two of the reviewers were employed at competing laboratories, and they did not follow standard procedure. Instead, upon receiving the manuscript, each of the two laboratories held a press conference to announce that they had invented this laser.

This misconduct led to the historical belief that the GE team was not the first, even though the record shows otherwise. Bob and his colleague had been the earliest to publish, and they were awarded the patent as well. As their historic paper stated: "While stimulated emission has been observed in many systems, this is the first time that direct conversion of electrical energy to coherent infrared radiation has been achieved in a solid-state device. It is the first example of a laser involving transitions between energy bands rather than localized atomic levels."

Dora and Bob. 50th anniversary. August 2, 1992.

Many years later, Bob and I were serving on some solid-state committee in Washington, D.C. When the meeting ended early, we had time before our scheduled flights home, so I suggested we visit the Smithsonian. Bob agreed, noting, “Years ago they asked me for my first semiconductor injection laser, and I always wondered what they did with it.” We took a taxi to the Smithsonian, found our way to the second floor, where lasers were featured, and were suddenly confronted with a 10-foot-high cardboard photo of Bob himself. He was struck dumb. It was part of a big exhibit about his laser, and about his work. He had no idea it was there.

I first met Bob when I arrived at the GE Semiconductor Laboratory, about a year after his injection laser project, with the ink still drying on my Ph.D. in theoretical physics. He immediately started to mentor me, and suggested that I pay attention to unexplained

Richard Hall, Elaine Schulz, Daniel Schulz, Dora Hall, Robert Hall. September 5, 1992.

semiconductor phenomena that needed elucidation through theoretical analysis. For example, he proposed that I investigate a semiconductor's energy gap, between the conduction and valence bands, which is changed by adding impurities. I accepted this challenge, and the paper I wrote on the subject became one of my most cited; another paper, also derived from a suggestion by Bob, examined how the energy gap changed with increasing temperature. And after Bob encouraged me to team up with a newly hired experimentalist, Jim Conley, to investigate electron tunneling in a newly discovered phenomenon—the Schottky barrier between a metal and a semiconductor—the collaboration with Jim proved very fruitful, establishing my career in solid-state physics.

Bob spent the early years of his own career learning how to add impurities to semiconductors. In its last decade, he reversed direction and learned how to grow semiconductors with the fewest impurities. All materials have impurities; crystals have them partly because they are grown at high temperatures, where foreign materials can easily diffuse in from the surface. In the end, having developed new methods of growing crystals and new methods of purification, Bob learned how to grow them with a thousand times fewer impurities than others had achieved. Stated another way, he was able to grow crystals in which only one out of 10^{12} atoms was an impurity. This amazing achievement has not been surpassed.

Richard Hall, Dora Hall, Elaine Schulz, Robert Hall. August 17, 2003.

Although Bob's interest was initially just scientific curiosity ("How pure can we make these materials?"), he soon realized an important application—ultrapure crystals as gamma-ray detectors in nuclear physics processes. Bob then helped GE develop what is now the standard technology for this application.

To see how difficult such ultrapurification really is, consider this story: I was talking to Bob in his laboratory one day while he was measuring one of his ultrapure samples. All of a sudden the measurements started changing rapidly, indicating that many new impurities were being added to the sample. Bob immediately shut down the procedure and went looking for the cause. He found it five doors down the hallway, where another scientist had uncorked a bottle with some gaseous material. It took only a few seconds for that gas to find its way into Bob's sample, many meters and a good length of hallway away. Bob politely asked the scientist to shut his lab door in the future, especially when uncorking bottles.

Over the course of his career, Bob was awarded 43 U.S. patents and wrote or coauthored 81 publications. He was a fellow of the American Physical Society, a fellow of the Institute of Electrical and Electronics Engineers, a member of the U.S. National Academy of Sciences, and a member of the U.S. Academy of Engineering. He received the Marconi International Fellowship, and was inducted into the Inventors Hall of Fame.

Robert Hall, undated late-career photo.

Bob was an inspiring colleague, and a great boss. We used to call him, behind his back, our "Boy Scout leader." He was the nicest person you could ever meet, and a true gentleman. Bob was not only the best scientist in the laboratory; he always had a smile on his face and a nice word for everyone. We all loved him.

One small example of Bob's thoughtfulness: While most scientists have one or more technicians in their laboratory to help them (as in taking measurements), Bob was a rarity in that he usually put their names on his publications. Today, journals do not allow coauthors who do only routine measurements.

Bob also had a full life outside the laboratory. Lean, wiry, and very fit, he was an active outdoorsman. In summer he hiked, swam, and sailed at his family vacation house on Hunt Lake, N.Y. During the winter months, he loved to ice skate. Upstate New York is blessed with a number of lakes, such as Round Lake, Ballston Lake, Saratoga Lake, and Lake George. Because each lake usually froze in the winter, but at different times, each of us "club members" was responsible for monitoring a given lake. When it would freeze to an ice thickness of four inches, we would all take the afternoon off and go skating. And it may not surprise you that Bob was the best skater.

Bob and his wife Dora (née Siechert) were married on August 2, 1941. They had two children, son Richard Hallock Hall and daughter Elaine Louise Schultz.

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