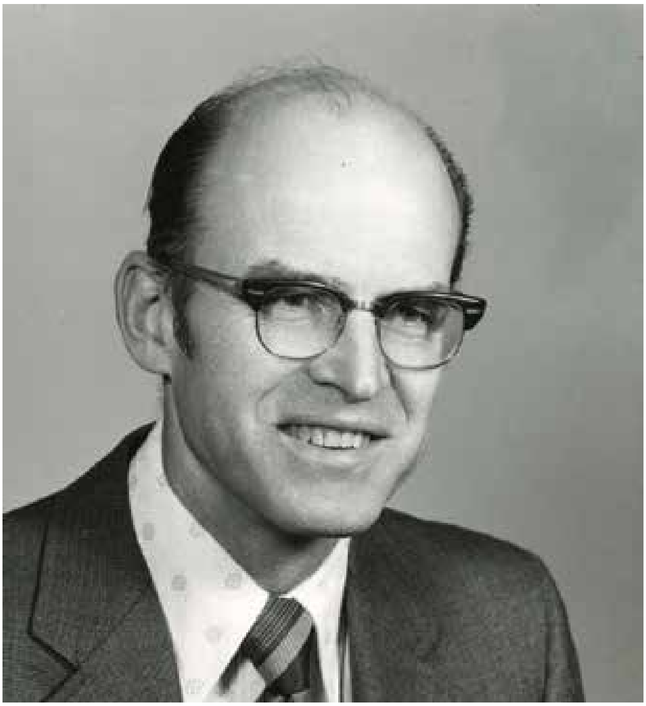

Robert N. Hall

ROBERT N. HALL

1919–2016

Elected in 1977

"Contributions to alloyed junctions, p-i-n, tunnel and laser diodes, and ultra-purification of semiconductors."

BY GERALD D. MAHAN
SUBMITTED BY THE NAE HOME SECRETARY

ROBERT NOEL 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, New York. He 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 for it, and authored the first publication about it. He also devised the principal method for making very-high-purity silicon and germanium, and used these materials to create a device for measuring nuclear radiation. He died November 7, 2016, at age 96.

Born December 25, 1919, to Harry and Clara Hall in New Haven, Bob attended the California Institute of Technology and graduated with a BS degree in physics in 1942. He returned to obtain his PhD in physics in 1948.

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In the intervening years he worked for Lockheed Aircraft (1940–41) and General Electric/Schenectady (1942–46) as a test engineer. 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 PhD, 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 now the basis for charging all portable electronic devices such as cell phones and laptop computers.

In the early days of semiconductor technology, germanium was the preferred material. The Bell Laboratory team of John Bardeen, Walter Brattain, and William Shockley invented the germanium transistor, but when a far-sighted 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, enabling them 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 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 standard practice around the world, but Bob and his colleague Jerry Tiemann, another GE physicist, were the first 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.

In 1962 Bob's GE team of Gunther Fenner, Jack Kingsley, Ted Soltys, and Bob Carlson was vying with 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 sent the manuscript out to review. But two of the reviewers were employed at competing laboratories and did not follow standard procedure: upon receiving the manuscript, the two laboratories each 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 also the first example of a laser involving transitions between energy bands rather than localized atomic levels."[1]

Many years later, Bob and I were serving on a solid state committee in Washington, DC. 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 PhD in theoretical physics. He immediately started to mentor me, and suggested that I pay attention to unexplained 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 and established my career in solid state physics.

Bob spent the early years of his own career learning how to add impurities to semiconductors. In the last decade of his career, he reversed direction and learned how to grow

[1] Hall RN, Fenner GE, Kingsley JD, Soltys TJ, Carlson RO. 1962. Coherent light emission for GaAs junctions. *Physical Review Letters* 9(9):366–368 (p. 368).

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 1,012 atoms was an impurity. This amazing achievement has not been surpassed.

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. He 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 hall, 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.

Bob was awarded 43 US patents and wrote or coauthored 81 publications. He was a fellow of the American Physical Society and Institute of Electrical and Electronics Engineers, and a member of the National Academy of Sciences as well as the NAE. He received the Marconi International Fellowship, and was inducted into the Inventors Hall of Fame.

Bob was an inspiring colleague and a great boss. He was not only the best scientist in the laboratory; he always had a smile on his face and a nice word for everyone. 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. 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 (for example, in taking measurements), Bob was a rarity in that he usually put their names on his publications. Today, journals do not allow coauthors who only do 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, NY; 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 they 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 4 inches, we would all take the afternoon off and go skating. Bob was the best skater.

Bob and his wife Dora (née Siechert) were married August 2, 1941; she died in 2013. They are survived by their two children, Richard Hallock Hall and Elaine Louise (Daniel) Schulz.