The following excerpts from the authors' book *Crystal Fire* track the work of an unsung hero of semiconductor history: Russell Ohl, the inventor of the pn junction

# The origins of the pn junction

MICHAEL RIORDAN & LILLIAN HODDESON

On the afternoon of 6 March 1940, Joseph Becker and Walter Brattain took an urgent call from Mervin Kelly, then director of research at the Bell Telephone Laboratories, who told them to come to his office immediately. The two middle-aged physicists, who had been studying thermionic emission and other surface effects together for a decade, were right in the midst of an experiment. When Becker objected that they had to finish their measurement, Kelly got adamant. "Drop it," he snapped, "and come on up here!"

A few anxious minutes later they reached Kelly's office, where they found several other group leaders and two men from Bell's radio department. One was Russell Ohl—a fortyish, elfin, balding, bespectacled Pennsylvania Dutchman who often seemed to have a merry twinkle in his eye. He certainly did that day.

On a table in front of Ohl was a simple electrical apparatus—a voltmeter and wires hooked up to a coal-black rod of material almost an inch long. It was a piece of silicon, an element whose behavior he had been studying for five years. It had two metal leads attached, one at either end. He picked up a flashlight, switched it on, and pointed its light beam directly upon the dusky rod.

Suddenly the voltmeter's needle sprang up to almost half a volt. Dumbfounded, Brattain shook his head in disbelief. It was an enormous effect—more than 10 *times* bigger than anything he and Becker had ever observed with any other photocell. Copper oxide and selenium rectifiers, often used at the time in exposure meters, would generate tiny voltages in room light—but nothing at all like this mysterious silicon rod.

"We were completely flabbergasted at Ohl's demonstration," Brattain later confided, stroking his bushy gray mustache. "I even thought my leg, maybe, was being pulled, but later on Ohl gave me that piece or another piece cut out of the same chunk, so I was able to investigate it in my own laboratory." Sure enough, he got the same astounding surge whenever he flashed light on the silicon.

Ohl's work on silicon stemmed from his interest in ultrashort-wave radio communications. As war approached, this area of work took on added urgency due to the fact that very short-wave radiation—especially at wavelengths less than a meter—was extremely desirable for use in radar. But generating and detecting these ultrashort waves was no mean feat at the time. Hundreds of scientists and engineers were working on these problems in Europe and the United States.

One of them was George Southworth, who worked with Ohl at Bell's field radio laboratory in Holmdel, N. J., about 20 km south of Staten Island. In the mid-1930s Southworth had been trying to detect ultrashort radio waves around a tenth of a meter long—what he then dubbed "hyper-frequencies" and are today called microwaves—using specially designed vacuum tubes. But he was having little success. Inherent time lags in the flow of electrons through the tubes were simply too great to cope with these extremely short, rapidly oscillating waves. Copper oxide rectifiers didn't work any better, either.

Frustrated, Southworth decided to try one of the old "cat's-whisker" crystal detectors he had used in radio sets during World War I, when he served in the Army Signal Corps. These quirky devices had fallen gradually out of favor when vacuum triodes became easily available during the 1920s. By the mid-'30s it was almost impossible to buy a crystal detector in an ordinary radio store.

So Southworth hopped a train bound for lower Manhattan, where he knew there was a second-hand radio market on Cortlandt Alley, south of Canal Street. Rummaging around on the dusty back shelves of one tiny shop, he soon found a few old cat's-whisker detectors. After bargaining with the shopkeeper, he carried them back to Holmdel, where he dusted them off and carefully inserted one into his receiving apparatus. He began searching around on its shiny surface for a suitable "hot spot," where the rectification was good. Finally, after hunting almost an hour, he found a good one. And it worked! At last, he could detect his ultrashort-wave, hyper-frequency radiation.




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Southworth told Ohl about his success, but it was no surprise, for Ohl had been using crystal detectors on and off for decades. Trained as an electrochemist at Penn State, he became interested in radio during the War, while serving as a lieutenant in the Signal Corps. After two years at Westinghouse, Ohl came to AT&T in 1922 and joined Bell Labs five years later, concentrating on radio. "I studied and reported what the situation was—the radio equipment situation," he said. "I kept the company knowledgeable with regard to the art."

Southworth had no difficulty convincing Ohl to make a comprehensive study of crystal detectors, in an effort to determine the best materials. Ohl tested over a hundred materials and found that silicon detectors, which he had occasionally used ever since making one during his college years, were by far the most sensitive. In the mid-'20s, in fact, he had experimented with short-wave reception while living in the Bronx:

> "I tried many kinds of receiving circuits, with peanut-type vacuum tubes and other special vacuum tubes, and none of them worked. So then I got out my old silicon crystal detector and used it. Lo and behold, it was sensitive as the dickens! And I could get reflections from the elevated lines [of] the West Side/ Yonkers, and the only way I could cart the receiver around was with Russ's baby carriage. I loaded that up with receiving equipment, and I went all around New York University with it. I was getting strong interference patterns from reflections from the elevated line from across the Harlem River on the West Side. There I began to appreciate the power of the crystal detector—this was the silicon detector."

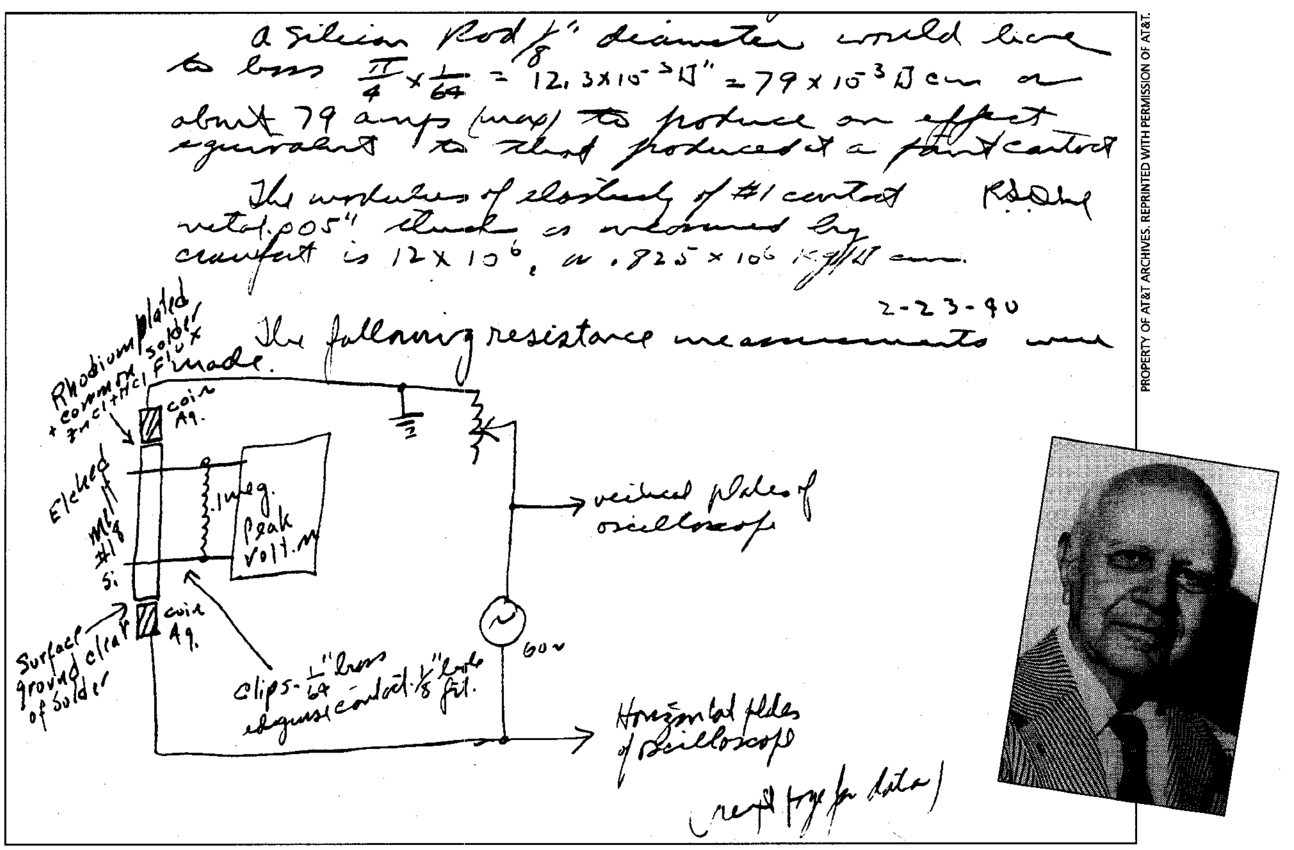
Two decisive events in semiconductor technology are chronicled in this article and the one following—Russell Ohl's discovery of the pn junction in the 1940s, and Gordon Moore's prophecy, in 1965, of exponential growth in IC complexity.

When Bell Labs went to a four-day work week during the depths of the Depression, Ohl used the time off to bone up on atomic and crystal structure. He was trying to figure out what made detecting materials behave the way they did. "I found that certain crystal structures were favorable," he recalled, "and usually the structures were made up of elements of the fourth group—valence four."

The elements of the fourth column of the periodic table are unique in that they can share their electrons with each other to form solid materials bound together by an extensive network of covalent bonds. The four electrons in one atom pair up with four electrons from nearby atoms in the crystal lattice to yield a filled atomic shell of eight electrons. Diamond and graphite are composed entirely of carbon atoms, differing mainly in how the atoms are arranged. Silicon and germanium form similar crystal structures—which by the 1930s had begun to intrigue Ohl, Southworth, and other radio researchers.

Silicon had been used for crystal detectors ever since 1906, when Greenleaf Whittier Pickard obtained a U. S. patent on the device. Carborundum, a combination of silicon and carbon used as a common abrasive, was another popular choice. These and other semiconducting materials, such as galena and pyrite, were used in the favorite radio detectors until the mid-'20s.

Radio operators hunted around on the surface of these






**On 23 February 1940, Russell Ohl [photographed in later years] sketched in his laboratory notebook the circuit that he used to measure the resistance of a silicon rod. The odd behavior of the current passing through the rod led to his discovery of the pn junction.**

materials using a metal wire—tungsten was eventually found to work best—to find hot spots where there was good reception. Today we know that this maddening variability was due to the polycrystalline nature of the materials and to differing impurity levels across the surface. But early in the twentieth century it seemed like black magic. "Such variability, bordering on what seemed the mystical," recalled physicist Fred Seitz, "plagued the early history of crystal detectors and caused many of the vacuum tube experts of a later generation to regard the art of crystal rectification as being close to disreputable."

Crystal detectors were made from the metallurgical-grade silicon that was commercially available during the '30s. Used as an agent in steelmaking, this commonly contained a few percent impurities, such as aluminum. And just as for cat's-whisker detectors of the '20s, you still needed to hunt around for good hot spots. "At that time you could get a chunk of silicon,... put a cat's-whisker down on one spot, and it would be very active and rectify very well, in one direction," noted Brattain. "You moved it around a little bit—maybe a fraction, a thousandth of an inch—and you might find another active spot, but here it would rectify in the other direction." At one spot current would flow only from the wire to the silicon, for instance, but not the other way. And vice versa at a different spot. Or not at all at another.

This erratic behavior of silicon detectors, guessed Ohl, occurred because of impurities. To get more uniform samples, he decided to try purifying silicon. In 1937 he obtained powdered silicon that was better than 99 percent pure from a German chemical company and tried to fuse it into a solid mass in his basement workshop. Then he enlisted the aid of a Bell Labs chemist who attempted to melt the raw silicon in a vacuum furnace, hoping the impurities would settle out of the liquid. But silicon liquefies at 1410 °C, which is hot enough to melt a lot of other materials, and impurities from the crucible walls could easily poison the molten silicon. In addition, the silicon usually cracked upon cooling, making it difficult to work with.

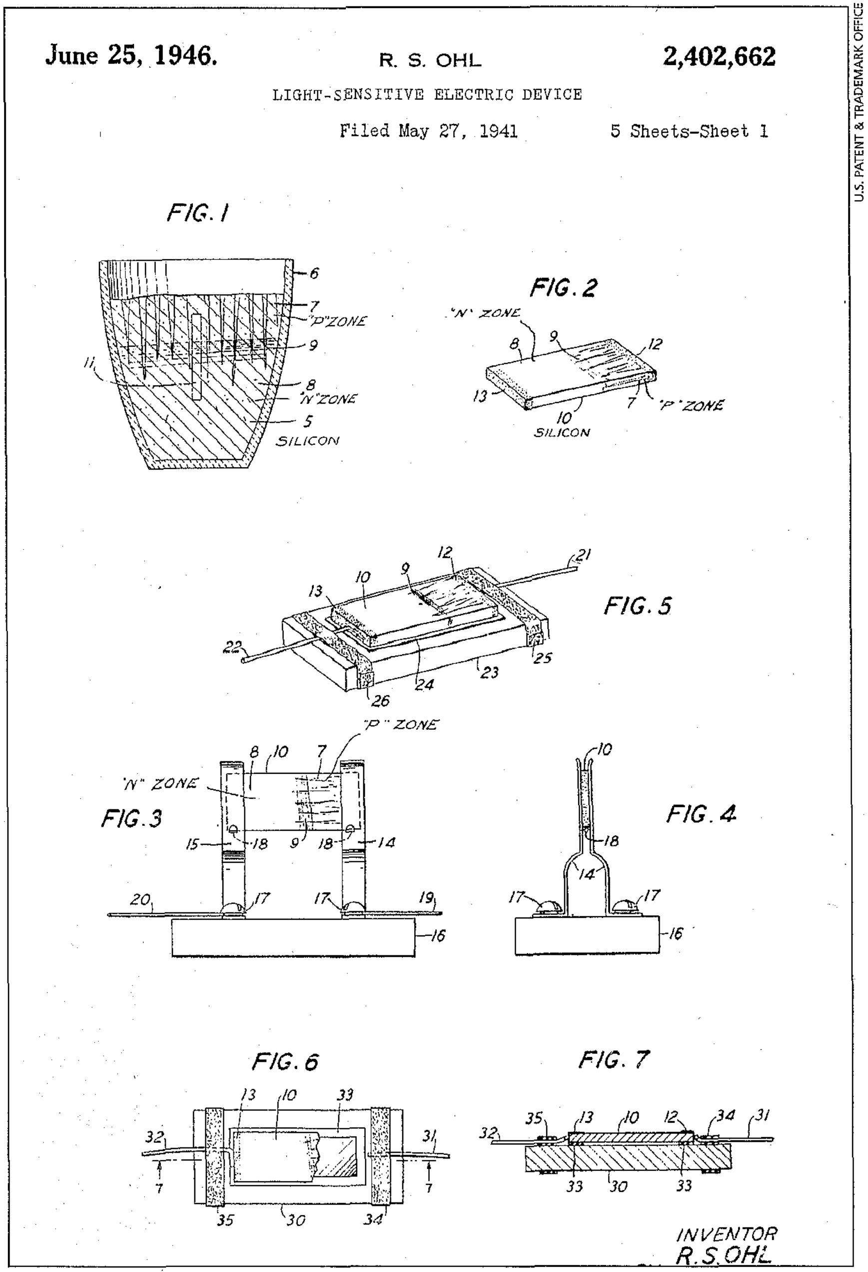
Ohl figured he needed a specialized furnace to help solve these problems. In August 1939 he got help from two Bell Labs metallurgists, Jack Scaff and Henry Theuerer. Using an electric furnace with an atmosphere of inert helium, they melted the silicon in quartz tubes. After the silicon had cooled and solidified, they cracked away the quartz to obtain black polycrystalline ingots.

Bringing these ingots back to Holmdel, Ohl had smaller pieces cut from them and began making electrical tests. The rectification properties, he found, were now much more uniform across a given sample. In certain ingots current flowed from the wire to the silicon, and in the rest it flowed the other way. But he still had no *a priori* way of controlling this behavior. The silicon ingots just came out of the furnace behaving in one manner or the other. "We recognized there were two types of silicon," recalled Ohl—one he called "commercial" and the other "purified."

In October Ohl sent Becker a few rods and disks cut from one of the ingots Scaff and Theuerer had prepared using 99.8 percent pure silicon. Ohl asked him to determine the conductivity of the samples. Becker soon returned one of the black rods, saying that he simply could not make any repeatable measurements on this sample. Its behavior was "so erratic that no consistent values could be reported."

Ohl installed the rod in the setup he normally used for testing silicon. He discovered that it generated a "peculiar loop" on his oscilloscope that "indicated the presence of some kind of barrier in the silicon." After discussing this oddity with his boss Harald Friis, he tried a few other tests, but without any encouraging results. Then he advised Scaff to raise the melting power of his furnace briefly, in order to produce more uniform ingots. The mysterious barrier was obviously something to avoid—a clear disadvantage in fabricating silicon detectors.

But Ohl paid no more attention to his malfunctioning rod until early the follow-

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The patent application filed by Russell Ohl and Bell Telephone Laboratories for a "light-sensitive electric device" shows a cross section of an ingot of fused silicon [upper left] and an electromotive force cell made from the ingot [upper right]. Other drawings show ways of mounting the device.

ing year. On Friday morning, 23 February 1940, he began to test how much current would pass through this rod. In his lab notebook he wrote that "near one end of the rod there is a change in the crystal structure indicated by a crack," which he figured might be responsible for the peculiar loop on his oscilloscope screen. Suddenly he noticed that the loop *changed shape* when the rod was placed above a bowl of water. And it did the essentially same thing near a hot soldering iron. This was a curious piece of silicon indeed!

By early afternoon, Ohl recalled in an unpublished memoir, "we had found that the loop was greatly effected [sic] by the presence of an incandesent [sic] lamp." Turning on a nearby 40-W desk lamp was enough to alter its shape. And when Ohl placed a light source behind a rotating fan, the loop pulsated at 20 cycles per second—corresponding to the frequency at which the fan's blades shadowed the silicon rod.

The following Monday he showed these peculiar effects to Friis, who was completely at a loss to explain why a small current began trickling through the rod whenever Ohl shone a light on it. This was obviously something to show the scientists at the West Street headquarters of Bell Labs; they understood solid-state physics much better. But Friis was reluctant to approach Kelly and reveal his ignorance. The two just did not get along. Ohl remembered Friis saying that the tough, aggressive research director had once made him "so mad that if he had had a pistol, he would have shot Kelly dead right on the spot."

The following week, however, Ohl ended up in Kelly's office demonstrating his mysterious silicon rod, surrounded by all the other scientists, including Becker and Brattain. Nobody had a clue about what was happening except for Brattain, who suggested a tentative explanation: the electric current must be generated at the barrier inside—just as happens when you shine a light on the barrier in a copper oxide rectifier. What truly amazed him was how *high* the voltage was in silicon. To his knowledge, he added, "this was the first time that anybody had ever found a photovoltaic effect in elementary material."

A small miracle had occurred serendipitously inside this innocent-looking silicon shard. Back in September when they produced the ingot from which the rod was cut, Scaff and Theuerer took great pains to cool it slowly, attempting to avoid the cracking that had often plagued previous ingots. Upon solidifying, the impurities inside the ingot separated spontaneously, leaving one portion near the center as "purified" silicon and another portion at the top as "commercial" silicon. In cutting out the rod Ohl sent to Becker, a technician unwittingly sliced right across the boundary between these regions. So one end of the rod behaved like purified silicon and the other end like the commercial grade.

At the surface where the two regions met, a barrier had formed that was much like the one that occurs at the interface between copper and its oxide. In effect, the silicon rod was itself a rectifier—which is one reason Becker had difficulty measuring its conductivity. The silicon on one side of the barrier was an "excess" semiconductor with extra electrons due to the impurities present there. On the other side there was an electron deficit due to other kinds of impurities; the silicon here was a "defect" semiconductor like copper oxide. The barrier arose when the electrons rushed from one side to the other in an attempt to neutralize the difference.

When Ohl flashed light on this barrier, the photons impinging on the surrounding material jarred additional electrons loose from their atoms, and those electrons were then free to scamper about. But because of the rectifying barrier there, the electrons could pass in only *one* direction across it, yielding the current and the large voltage observed by Bell's mystified scientists and engineers. This was the big photovoltaic effect that astounded Brattain and the others. Little did they realize it at the time, but they were witnessing the immediate ancestor of modern solar cells.

While Brattain rose mightily in Kelly's esteem because of his impromptu explanation of this photovoltaic effect, Becker suffered from missing it, said Ohl, "because he had that active silicon in his department, in his hands, and he didn't find it."

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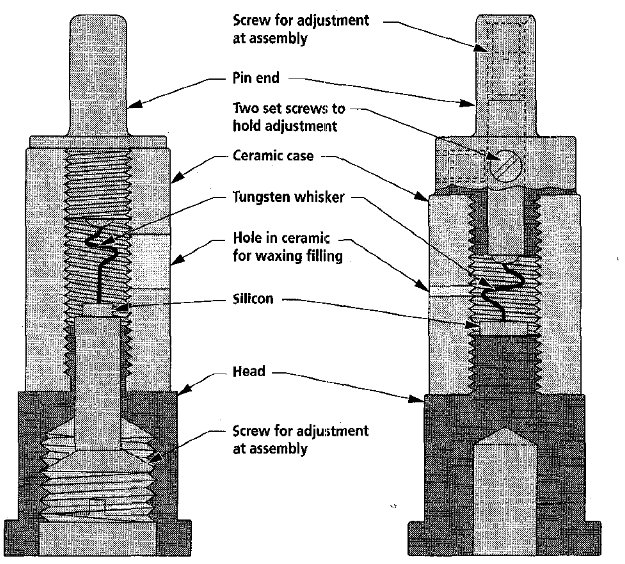
In late March Scaff decided to take a closer look at the ingot from which Ohl had cut the photoactive silicon rod. With the help of a technician, he determined that the ingot had cooled slowly from its top surface down into its center. What's more, after treating it with nitric acid for several minutes, they discovered a clear-cut *dividing line* part way down into the ingot—right where the rod had been cut out of it. Below this line was the "purified" type silicon, while the silicon above the line behaved like the "commercial" grade. As Ohl recorded in his notebook on March 25:

> A point contact moved along the sides [of a silicon slab cut vertically from the ingot] at Mr. Scaff's suggestion yielded very distinctly (1) purified silicon characteristics near the bottom end of the slab (2) high resistance with negligable [sic] current... in the active photo electric region (3) commercial silicon characteristics near the top of the melt.

Right between the first and third regions was the actual barrier that Ohl and Brattain had suggested might exist. And you could even *see* it!

Recognizing that they had stumbled across an important phenomenon, Ohl and Scaff decided the two types of silicon needed names that corresponded better with their physical behavior. They coined the terms "p-type" (for positive) and "n-type" (for negative) to denote these two distinct regions "since in the top part of the ingot the easy direction of current flow occurred when the silicon was positive with respect to [a] point contact..., and in the lower portion of the ingot the converse was true." In addition, p-type silicon gave a positive voltage when illuminated, while a negative voltage arose with n-type silicon. The high-resistance,




Source: Henry C. Torrey and Charles A. Whitmer, *Crystal Rectifiers* (1948).

**Silicon crystal rectifiers played an important role in World War II as the key components of radar receivers. These drawings are cross sections of crystal rectifier cartridges produced by Sylvania [left] and Western Electric [right] during World War II.**

photoactive barrier between the two types became known as the "pn junction." It seemed a natural choice.

Ohl, Scaff, and Theuerer gradually began to suspect that the unusual effects were due to small impurities remaining within the high-purity silicon samples. A sample from one manufacturer behaved the same way from ingot to ingot, but two distinct samples from two suppliers behaved quite differently. That result would occur if these two samples contained different impurities—and if impurities strongly influenced the electrical behavior of silicon. During the slow cooling of the mysterious ingot that gave the photoactive rod, the 18th ingot fused by Scaff and Theuerer, these impurities should have risen or fallen in the melt, according to their different atomic weights. Lighter impurity atoms would congregate at the top of the ingot, causing p-type behavior, while heavier atoms would gather at its center and yield n-type.

"We became convinced that these effects were due to the segregation of impurities," Scaff reminisced, "though the specific impurities were not then known." Later the Bell metallurgists detected tiny amounts of boron—a very light element that appears just to the left of carbon in the periodic table—in the p-type silicon. Aluminum, which sits right below boron and immediately left of silicon in the table, is another light impurity that they found induced p-type behavior.

Determining what impurities caused n-type silicon proved to be a little more involved. Scaff and Theurer had noticed a peculiar odor whenever they broke predominantly n-type ingots out of the quartz tubes. So did Ohl when he cut them with his diamond wheel. According to Brattain, this odor was "very much like the smell you used to have on these acetylene lamps that you had on automobiles before [they] had electric lights."

Theuerer recognized that this odor was not due to the acetylene itself, however, but to tiny traces of phosphine gas that occurred due to impurities of phosphorus—an element that is slightly heavier than silicon and appears just to the right of it in the periodic table—in the acetylene. "By their noses they were detecting concentrations of phosphorus way below the spectroscopic limit," marveled Brattain. The minute phosphorus impurities had migrated to the center of the solidifying ingots, gathering there to produce n-type silicon.

Thus it gradually became known during the early '40s that the elements from the third column of the periodic table—just to the left of carbon, silicon, and germanium—led to p-type silicon, while elements from the fifth column such as phosphorus yielded n-type. The visible barrier or pn junction in the photoactive rod marked the dividing line between the two types: one with more third-column than fifth-column impurities, the other with excess atoms from the fifth column. Boron and aluminum somehow created gaps in the crystal structure of silicon, a lack of electrons, while phosphorus impurities contributed a surfeit. "We knew that there were holes on one side as in copper oxide," said Brattain, "and it was electrons on the other side."

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After March 1940 Kelly asked Becker and Brattain to play a role in Bell's silicon research effort, which he accorded greater and greater priority as World War II deepened that year. Having headed Bell's vacuum-tube development before he became research director, Kelly spent large sums trying to develop small, fast vacuum-tube detectors for use in radar. Finally he gave up when these efforts proved futile and silicon looked much more promising.

Silicon crystal detectors became a key component of radar receivers during the war. They served the crucial function of converting high-frequency, short-wave radar signals into lower-frequency oscillations that could be more readily amplified in electronic circuits. At ultrashort wavelengths of a tenth of a meter or smaller—the so-called centimeter or microwave range—vacuum tube and copper oxide rectifiers were essentially useless. Silicon (and later germanium) crystal detectors proved to be the only hope. By sharpening their point contacts, engineers could make them sensitive at ever shorter wavelengths and achieve excellent detection of microwave signals.

Kelly's enlightened, forceful leadership played no small part in the success of Bell's wartime radar program. He alternately bullied and cajoled the best possible work out of his men, who frequently tiptoed around him, afraid of his legendary Irish temper. "When provoked, he would turn dark red, but a moment later he would be normal again," remarked John Pierce, inventor of the traveling-wave tube. "I did not seek him out for fear of being struck by lightning." One Bell Labs vice president confided that he "learned never to oppose him when he had the bit in his teeth," preferring to discuss the matter calmly a day or two later when Kelly would be more approachable.

The British, too, had recognized that silicon crystals make good detectors of microwave radiation. During 1939–40 electrical engineer Denis Robinson and physicist Herbert Skinner, working with the Telecommunications Research Establishment—Britain's equivalent of the Radiation Laboratory (Rad Lab) at the Massachusetts Institute of Technology—developed a cat's-whisker crystal diode made from metallurgical-grade silicon doped with tiny amounts of aluminum. By late 1940 the British Thompson-Houston Co. and General Electric Co. were beginning to manufacture these detectors in small cartridges that could be readily inserted into radar receivers. But these firms still used commercially available silicon, which contained impurities of a few percent that led to unpredictable detector performance. Before sealing a cartridge, production workers hunted around on the silicon surface for a good hot spot; then they tested them all and kept only those that worked well.

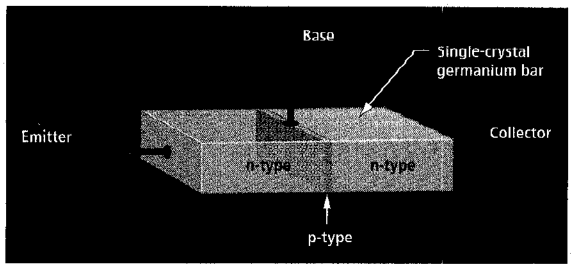
"Unfortunately, the units…tended to differ radically from one to another and, on occasion, to behave erratically," remembered Seitz. Early radar operators would commonly carry a number of such cartridges with them "and search for one that worked, replacing it with another if and when it stopped functioning or became erratic." During 1941, working at the University of Pennsylvania under a contract with the Rad Lab, Seitz and a group of coworkers developed a chemical process with du Pont that yielded extremely pure silicon—99.99 (and eventually 99.999) percent pure, or only 100 parts per million in impurities. Carefully controlled amounts of aluminum or other elements could then be added to this "4–9" (and later "5–9") silicon to achieve the very uniform, predictable electrical characteristics needed to mass-produce crystal detectors.

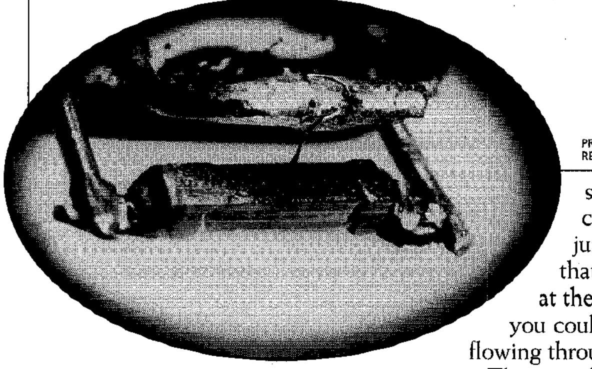
This ultrapure du Pont silicon was in great demand among the scientists and engineers working on crystal detectors. Through the Rad Lab, Ohl managed to get several pounds of it every few months. This was enough for his research efforts, which included how to cut, etch, and polish the doped silicon wafers—and how best to attach metal contacts to their back sides. Scaff concentrated on large-scale development work, including how to mass-produce large volumes of p-type silicon for use in Western Electric's manufacturing plants.

Bell also sent substantial quantities of its silicon to other U.S. institutions working on crystal detectors. Some even went to the British scientists who were working closely with U.S. researchers through the Rad Lab. "We were sending samples to them, as well as samples of our detectors, over in the diplomatic pouches, as well as complete technical information," said Scaff. British and U. S. scientists, Seitz among them, often visited the Labs to discuss the latest advances.

Wartime urgency encouraged a remarkably open sharing of information among the expanding network of scientists and engineers working on crystal detectors—all, of course, under the dark umbrella of military secrecy. Members of the network attended "crystal meetings" every two months or so, first at Columbia University and later in the Empire State Building, to review research in progress and to compare notes.

But Kelly embargoed any talk outside



**The invention of the junction transistor in the late 1940s was founded on Russell Ohl's discovery of the pn junction. The photo shows the first npn transistor, a germanium device, invented by William Shockley in January 1948. The first transistor, a point-contact device, had been invented by Walter Brattain and John Bardeen a month earlier.**



Bell Labs on one matter—the pn junction. It was too important a breakthrough to bruit about. "I had to take the melts that were produced and cut the junctions out of them—cut the n-type material out of it and send the remaining p-type material to the British to fabricate," Ohl said. "We did not break the confidential basis of the company information and turn that over to the British."

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For the rest of the war, only a select circle of researchers—mostly at Bell Labs—knew anything about pn junctions. Although Bell attorneys applied for patents in 1941, the information remained classified until 1946, when on 25 June a series of four patents were awarded in Ohl's name on silicon detectors and pn junctions. Another was issued that same day to Scaff for the silicon-processing techniques used to form these junctions.

Meanwhile, Kelly had been marshalling his troops for the postwar battle that, he reckoned, would erupt in electronics due to the wartime advances in microwave and semiconductor technologies. "All of this art has been made available to a large sector of the radio industry," he observed in a 1943 memo. "The struggle for markets will continue to force the development of low-cost techniques."

In the spring of 1945 Kelly began preparations in earnest, luring his brilliant protégé William Shockley back from war work as a military consultant to head a new solid-state physics group at Bell Labs. On 24 March Kelly brought Becker, Shockley, and several more over to Holmdel for a briefing about Ohl's silicon research. Shockley was especially intrigued by the pn junction. "Did you ever think that if you put a point contact at the barrier," he asked Ohl, "that you could get control of the current flowing through?"

Three weeks later Shockley began writing down ideas in his lab notebook about how one might make a semiconductor amplifier—or, as he called it, a "solid-state valve"—by applying electric fields across a pn junction. "It may be that the type of device considered here can be made of Silicon with Boron & Phosphorous [sic] impurities," he conjectured on 16 April. Although this "field-effect" approach, which was tried by Bell Labs technicians during the next two months, yielded no measurable amplification, it stimulated a research program that eventually led to the invention of the point-contact transistor by Brattain and solid-state theorist John Bardeen in December 1947.

But Shockley was chagrined because he had had no direct role in what he recognized was a critical breakthrough. "My elation with the group's success was tempered by not being one of the inventors," he recalled many years later. "I experienced frustration that my personal efforts, started more than eight years before, had not resulted in a significant inventive contribution of my own."

Galled at being upstaged by members of his own group, Shockley began a month-long bout of feverish activity that resulted in his invention of the pn junction transistor on 23 January 1948. His design involved two pn junctions separated by a thin strip of p-type semiconductor that served to control the flow of electrons between the surrounding n-type regions. When techniques to make such bipolar junction transistors in germanium were at last perfected three years later, electronics manufacturers in the United States and Japan quickly seized upon Shockley's approach as the obvious way to proceed.

Today pn junctions permeate microchips almost as oxygen molecules permeate air. They are one of the three or four fundamental structures without which the modern semiconductor industry would not exist. If the transistor is the "nerve cell" of the Information Age, as Shockley so presciently recognized in 1949, then the pn junction is its DNA. Billions of them are generated daily in Silicon Valley alone.

Yet the name of its inventor remains largely unknown to the many who benefit from his crucial breakthrough. Part of the reason for this obscurity is the wartime secrecy that enfolded his work for half a decade. And for some odd reason his contribution was all but completely overlooked in the efforts of Bell Labs to spread the word about the transistor, solar cell, and other semiconductor devices based on his discovery. Perhaps now, with the publication of our book *Crystal Fire*, Russell Ohl will finally get the recognition he long deserved. ◆

## To probe further

Walter Brattain's recollections of Ohl's discovery and its impact on his work appear in "Discovery of the Transistor Effect: One Researcher's Personal Account," printed in *Adventures in Experimental Physics*, Vol. 5 (1976), pp. 3–13.

In *A History of Engineering and Science in the Bell System: National Service in War and Peace (1925-1975)*, the second chapter, "Radar," pp. 19–131, is a semitechnical survey of Bell Labs' contributions to the development of radar in World War II. Edited by M. D. Fagen, it was published by Bell Telephone Laboratories (Murray Hill, N.J., 1978).

Daniel Kevles's "A Physicist's War," in *The Physicists*, pp. 302–323 (Vintage Books, New York, 1979), gives a literate account of the involvement of U.S. physicists in military R&D projects during World War II.

Jack H. Scaff and Russell S. Ohl wrote, "The Development of Silicon Crystal Rectifiers for Microwave Radar Receivers," in *Bell System Technical Journal*, Vol. 26, no. 1 (January 1947), pp. 1–30; and J. H. Scaff wrote "The Role of Metallurgy in the Technology of Electronic Materials," in *Metallurgical Transactions*, Vol. 1 (March 1970), pp. 561–73. Both are technical papers that describe wartime developments at Bell Labs in silicon crystal rectifiers and pn junctions.

"Research on Silicon and Germanium in World War II," *Physics Today* (January 1995), pp. 22–27, is a very accessible account by Frederick Seitz of wartime semiconductor research outside Bell Labs, in Britain and elsewhere.

Henry C. Torrey and Charles A. Whitmer's *Crystal Rectifiers* (McGraw-Hill, New York, 1948) is the classic treatise on the development of crystal rectifiers during World War II, emphasizing work done at the Massachusetts Institute of Technology's Radiation Laboratory.

*Spectrum* editor: Linda Geppert