JOHN BARDEEN AND THE POINT-CONTACT TRANSISTOR

It is not widely appreciated that Bardeen first recognized minority-carrier injection, which is the basis for the original bipolar transistor and the beginning of modern electronics.

Nick Holonyak Jr

To this day it is not well understood that the bipolar transistor began with John Bardeen and Walter H. Brattain's point-contact transistor.[1] The invention of the point-contact transistor was a momentous event, not only in itself but even more because of the unimaginable revolution in electronics that followed. This revolution, which continues unabated, had a beginning: Bardeen's recognition of minority-carrier injection—that is, his realization that an applied voltage causes valence band holes from the surface region of an n-type semiconductor material near a metal contact to be injected into the bulk of the material. This realization made the semiconductor suddenly important and no longer just an interesting material to study.

The historic recognition of minority-carrier injection was followed a week later by the famous 23 December 1947 demonstration to Bell Telephone Laboratories "brass," as John called them, of transistor amplification and audio operation.

My main purpose in this article is to report largely unknown information from conversations, lectures, seminars, interviews and so on concerning Bardeen's identification, based on his work with Brattain, of minority-carrier injection and his invention with Brattain of the point-contact transistor, the prototype for all succeeding injection devices.

It is worth recalling that in 1947 the state of semiconductor knowledge and technology was, to say the least, primitive. Crystal quality was poor, and it was not even known whether germanium, the original transistor material, was a direct-gap or indirect-gap semiconductor.[2] It was finally determined to be the latter in 1954. This property turned out to be fortuitous in that it gave long enough minority-carrier lifetimes to permit realization of the point-contact transistor, which was the original bipolar transistor.[1,2] Besides starting a revolution in

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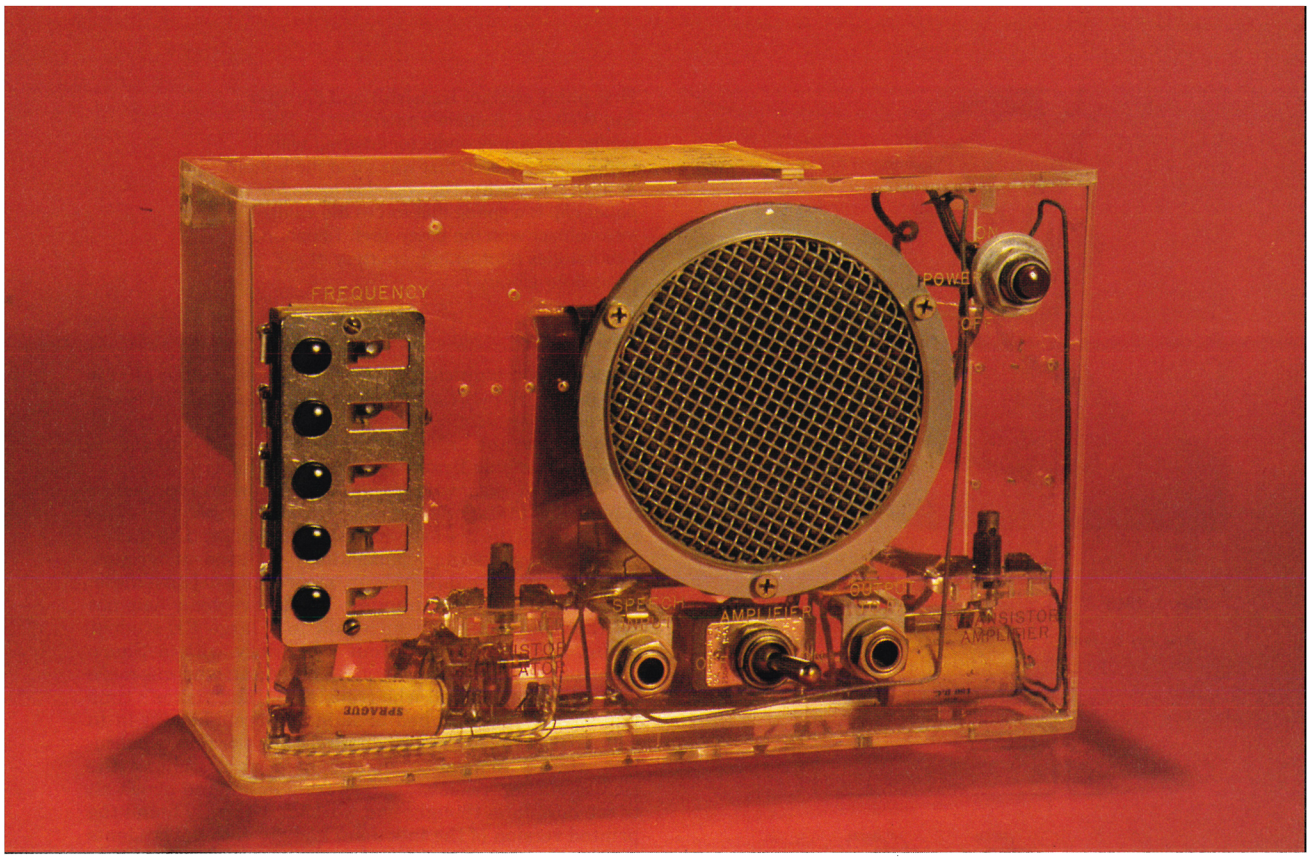


Famous 'box' used to demonstrate transistor operation. It contains an oscillator–amplifier circuit that uses two point-contact transistors. Three of these demonstration boxes, which were among the first transistor circuits ever constructed, were made in 1949. Their instant "turn-on" impressed audiences used to waiting for tubes to warm up. All the components were what existed at the time for vacuum tube circuits. Bardeen's box, pictured above, still exists, still operates and may be the world's oldest portable transistor circuit.

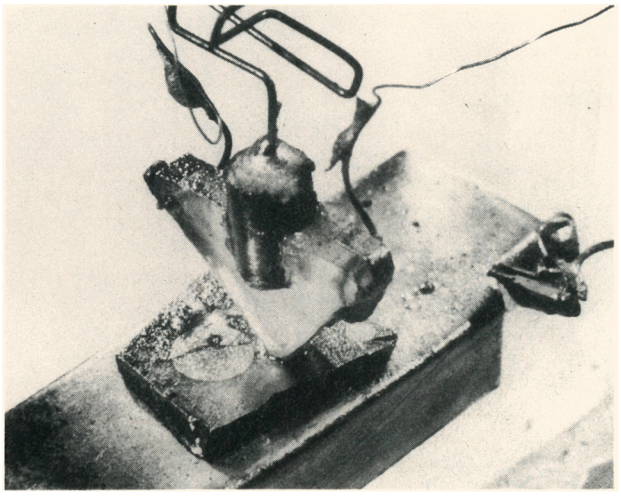
electronics, Bardeen's work marked the beginning of a new level of work on crystals and on materials in general. In tracing the history of Bardeen's work, it is important to recollect his famous 1947 paper on surface states, his concern with semiconductors with bent energy bands and the resulting need to deal with electrons and holes on an equal footing.[3] John was unique and maybe the only right person to be able to recognize minority-carrier injection.

Classroom lectures

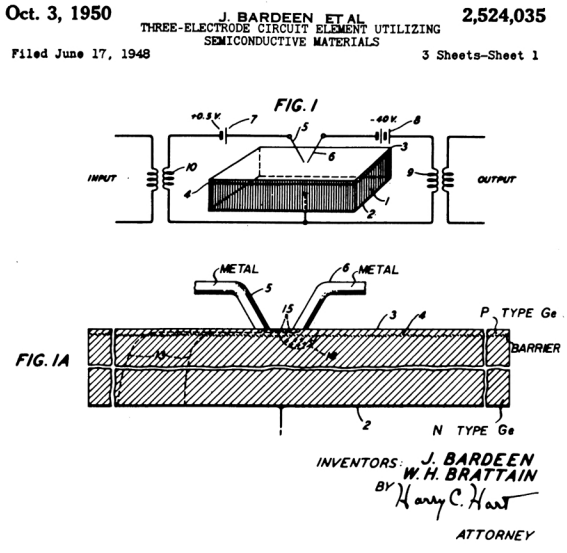
The year 1991 marked the 40th anniversary of Bardeen's leaving Bell Labs and coming to the University of Illinois. I was already a graduate student in the electrical engineering department at the university when he arrived, and in the fall of 1951 I took an atomic physics course that he taught. It was around this time that I first saw a transistor—and for the first time witnessed the instant "turn-on" of a device. Bardeen gave an electrical engineering seminar and demonstrated transistor operation with a portable oscillator–amplifier circuit employing two point-contact transistors. (The famous demonstration box is shown above.) The legend, perhaps unwarranted fiction, that John was not a very good instructor had not yet started. I was pleased with what I was learning from Bardeen, and even though ill prepared, not yet having had a course in quantum mechanics, I took the next course he offered, and was the only EE graduate student to do so. That was Bardeen's spring 1952 semiconductor–transistor course, which he taught from his notes and William Shockley's 1950 book *Electrons and Holes in Semiconductors*. It was perhaps the first time such a course was given at an American university, and to be sure, more postdocs than graduate students were in attendance.

I cannot recall the entire contents of John's course, but his lecture on the metal–semiconductor contact, or Schottky barrier, was unforgettable. He held his notebook open, his left arm bent upward underneath it to pull it up to his chest, and sketched the energy diagram of the metal–semiconductor contact (see the figure on page 39) on the left side of the blackboard, just in front of where I sat. He described the usual problem of electron flow via the barrier from metal to semiconductor or from semiconductor to metal. He turned to us and pointed to the valence band edge of the n-type semiconductor near the contact, where it approached the Fermi level. With a slight smile he said, "If Schottky in the '30s had looked here to see what the holes were doing, the transistor would have been invented." Over the span of 40 years, from 1951 to 1991, I got to know Bardeen well enough to know that he would never say directly that he had bothered to look and had determined what the holes were doing. That was not John's style. However, if someone else had recognized minority-carrier injection, he would have mentioned who. I am convinced John made the crucial identification, and he told us as much in his own way in EE-PHYS 435.

It was particularly not Bardeen's style to overtly point



First point-contact transistor and Bardeen and Walter H. Brattain's patent for it. The wedge was a nonconductor covered with a conducting foil strip that was slit at the bottom to form two leads. The wire that looks like a paper clip is a spring that forces the wedge into contact with the base. (Bell Telephone Laboratories photograph; courtesy of AIP Niels Bohr Library.)



at himself or to take credit for an important idea if doing so would take anything away from a close partner, in this case Brattain. John Bardeen knew that he was John Bardeen, and I don't think it mattered to him if others knew it. On the occasion of one of Brattain's Illinois visits, when I was still John's student, Brattain referred in a seminar to one of the Bardeen and Brattain papers and remarked that every time he read it he learned something further. It was obvious how the Bardeen–Brattain partnership worked: Bardeen liked working with experimenters and sorting out the data firsthand, not after others had perhaps confused the basic ideas.

During the last 28 or so years, since I returned to Illinois from General Electric, it was not uncommon for Bardeen to call me for short discussions and to walk into our laboratory for longer ones. As the years progressed and John and I got older, our discussions increasingly involved more sensitive matters. When Walter died in 1987, John called me, and unlike in his usual brief calls, I thought he would never get off the telephone. I tried to cheer him up, but he was heartbroken in spite of the fact that his partner's mental abilities had been lost for many years and communicating with him was difficult or almost impossible. When Bardeen told us in class in 1952 about the metal–semiconductor contact and minority-carrier injection and the basis for transistors, he did it in such a way as to include Brattain, not exclude him.

Bardeen was very generous: He was approached frequently to talk about the early days of solid-state research and the discovery of the transistor, and he was always accommodating, particularly to student groups. Every one of these talks was an opportunity to learn more, to see more of John's thinking. About five years ago, not all that long after one such talk to a large EE student group, John walked into our laboratory with a Sharp Electronics vice president and his assistant, who was more able with English and who translated. The visitor's time was short, and John had presumably brought him in to talk about semiconductor research, but the Sharp executive wanted instead to sit and hear at first hand the semiconductor–transistor story from John, and above all to see how John thought and worked. I quickly found the printed version of the talk John had given to the students and handed it to the visitor, but that wasn't good enough. He wanted to question John, and he asked which theoreticians had most influenced and helped John's work and thinking. John, smiling in his own special way, said he chose generally to work with experimenters, not theoreticians, and to see the facts, sort out the data and make suggestions accordingly. He didn't say that any theoretician had had much to do with his thinking on semiconductors.

NHK interview

To my knowledge, the last time Bardeen gave the semiconductor–transistor talk was to an honors class of students in the spring of 1990. I asked our graduate students to attend, because something new or fresh or different always emerged. This particular talk was very difficult for John because of serious problems he was having with his vision.

Not long after, he called me to help him with an interview he had agreed to do with NHK, the Japanese television company. John had planned that we would go to his home, and NHK could film while he and I talked about early work. But this arrangement did not suit the NHK people, who wanted to film in John's office and to conduct an interview. This was not an easy undertaking on a hot June day with four or five NHK employees and lots of TV and audio equipment crowding John's office. John always had a good notion of what he wanted to do, and now the NHK people had derailed his thinking. As he was gathering his thoughts and thumbing through his notes and figures, I quickly suggested to him that he could go through the viewgraphs of his recent student talk while NHK cameras recorded him. That is in essence what occurred, but it was not easy for John. After an hour or so I interrupted to ask if he needed a rest, but he preferred to press on.

During the session John went through most of the

story of the field-effect experiments he and Brattain had tried in 1947 and explained how they led to the transistor. John mentioned that it was well known at the time that increasing the temperature of a semiconductor increased the electron–hole population and that shining light on a semiconductor increased the carrier population, but it was not known that a current could be used to change the carrier population. I did not recall hearing this particular comparison before, even though John had used it. I couldn't let this go by, so I interrupted: "Then, John, you can put an exact date on when man first observed carrier injection." He looked at me and nodded while NHK filmed both of us, and then said, "Yes, a week before the famous demonstration to the BTL 'brass' showing amplification and audio operation." In my view that observation was the beginning of modern electronics: It was the magic moment when the semiconductor became important—when it became possible to make a semiconductor amplifier.

The next day John called to ask if I thought his presentation was at all good—it was. He then admitted that he was very tired during the filming. Something told me to take notes. I think I was beginning to sense that not only was John past 80, but his health was failing. This taping was the last time, to my knowledge, that John described the early semiconductor and transistor work. (I wrote to NHK for a copy of the unedited videotape for historians to use in the university archives, but in over a year I have not received a response.)

Office and laboratory discussions

Of course, over the many years that I was Bardeen's student and, subsequently, his colleague and friend, I saw him on many occasions in his office, in our laboratory and in seminars. Soon after Shockley's death in August 1989, John called me to come to his office to comment on a fax the Institute of Electrical and Electronics Engineers had sent him concerning Shockley. John did not want to write a statement about Shockley, because he felt out of touch with him. They had not worked together or had much contact for many years. Nevertheless he was concerned that Shockley be accorded proper recognition for his work on semiconductors. I took a copy of the fax home to read. That evening I looked in my copy of Shockley's book—my 1952 textbook—and reread the preface, including the following sentences:

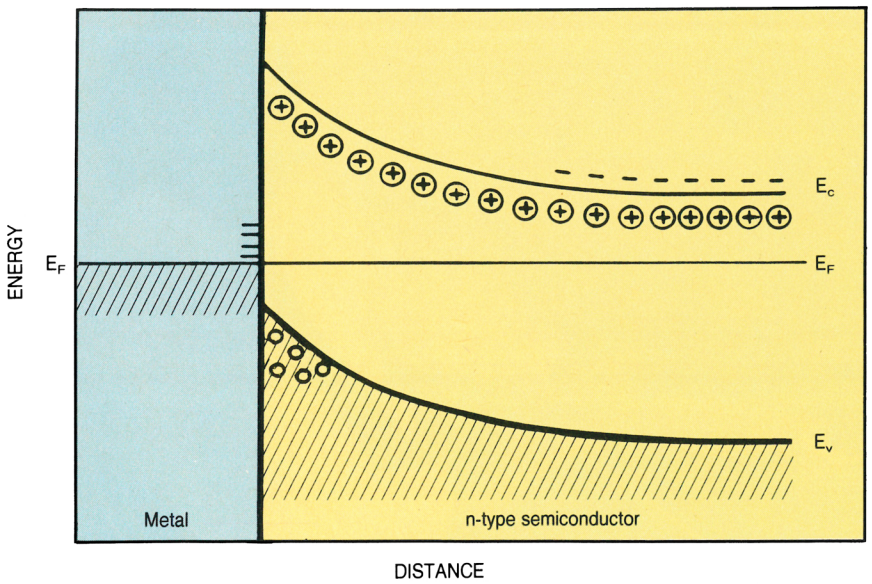
> This book had its origin in a series of lectures given at Bell Telephone Laboratories in connection with the growth of the transistor program. It thus owes its existence basically to the invention of the transistor by J. Bardeen and W. H. Brattain.

I told John the next day in his office that I had read Shockley's preface and the IEEE fax, and there wasn't much that I would change. Concerning the statement in Shockley's preface, I said that many people were still confused about who invented the transistor, but even Shockley's book admitted it was Bardeen and Brattain. John looked at me strangely and said I should read the statement Shockley had written in John's copy of the book, which was right there on the shelf. I was sure I could memorize it at the time, but later, when NHK was filming, I reached for the book and, to be certain, copied into my notes the inscription:

> To John Bardeen,
> Who made a book like this a need.
> Bill Shockley Dec 1950

I think it is clear what this means.

On an earlier occasion I mentioned to John that I had



Barrier layer at metal–semiconductor contact. The curves E_c, E_F and E_v in this energy diagram are the conduction band edge, the Fermi level and the valence band edge, respectively. Minus signs represent electrons in the conduction band; plus signs in circles, fixed positive charges; circles, holes. Horizontal lines represent surface states. Bardeen recognized that application of a voltage causes holes, or minority carriers, to move from the surface region of semiconductor material near a metal contact into the interior of the material while remaining in the valence band (down and to the right in the diagram).

been called on two separate occasions, years apart, by an IEEE committee concerned with awarding the Medal of Honor to Shockley. Both times there was confusion, because the citations credited Shockley with the invention of the bipolar transistor, which was not correct.[1] On the first occasion the matter was dropped because of committee arguments over Shockley's ideas on race. On the second occasion the medal was in fact awarded to Shockley. As I had the first time, I cautioned the committee representative who called me that the citation should not credit Shockley with inventing "the bipolar" transistor.

Incidentally, somewhere in our discussion of the fax from IEEE, John mentioned that he had recognized from the beginning that the transistor was not a device like the vacuum tube or, later, the field-effect transistor, and that recognition motivated John to devise the terms "emitter current," "collector current" and "base current." Bardeen's terminology for the currents in bipolar devices is now used universally. It is ironic that many users of junction transistors, which came later, do not appreciate this. Very simply, carrier injection and transistor electronics as we know them today began with the point-contact transistor, as did the terminology that rightly persists.

Kikuchi visit

In his succinct statement concerning Bardeen's life and work, Philip Anderson states that John left Bell Labs because of "the need for freedom from 'transistoritis.' "[4] This statement is more or less incomplete, as the following story shows. Representatives of Sony Corporation came to Urbana in September 1989 to establish the John Bardeen Chair in Physics and Electrical and Computer Engineering at the University of Illinois. I picked up John (because of his vision problems and the difficulty he had driving at night) and we went to the airport to meet Sony's Makoto Kikuchi, a longstanding friend whom John had met in Tokyo in the early 1950s. I, as a soldier, had been introduced to Kikuchi by John in 1956. Before I took Kikuchi to his hotel, John wanted us to stop at his home to visit a little. Sooner or later we were bound to talk about semiconductors and transistors and how they changed the world of electronics—in fact, changed the world. Indeed, because of the transistor, here was Sony—not a US corporation—coming to Urbana to fund a chair in Bardeen's name. During the course of the evening, Kikuchi asked John very specifically, very directly, "Why did you leave Bell Labs?" John answered that he had approached the "brass" at Bell Labs to set up another group, a theory group, and they turned him down—and he left. So it was more than just "transistoritis."

Bardeen did not give up his interest in semiconductors, even though over the years superconductivity and various related areas of theory—for good reason—claimed more and more of his interest and time. John decided to move over to emeritus status in 1975 to free a position for a younger person in a time of tight budgets. He didn't want a retirement party but did agree to a small research symposium involving colleagues and friends. When the planners, mostly theorists, showed him the program, it had nothing dealing with semiconductors. John immediately asked about the absence of semiconductor work. This was indeed a serious omission, and the task of inviting speakers on semiconductors was hurriedly handed to me. (I thought we should hear about quantum well heterostructures and superlattices, and after some persuasion Morton Panish agreed to describe progress in molecular-beam epitaxy at Bell Labs.)

Importance of the point-contact transistor

Although I can cite many more examples of John's interest in semiconductors, I want to return to point-contact transistors, such as those shown in the figures on

Bardeen in his office in the physics building at the University of Illinois at Urbana–Champaign. This photograph was taken in November 1973.

Bardeen and Holonyak in Holonyak's laboratory in 1973. Holonyak is holding a series circuit of InGaP LEDs emitting red, orange, yellow and green light.

pages 37 and 38. It has apparently been stated, and repeated rather casually, that the point-contact transistor was a "retrograde development," was "only partly a solid-state device" and "set back the cause of electronics."[5] Whatever the origin of these statements, they are wrong. Carrier injection and semiconductor amplifying devices did not exist before the point-contact transistor. To say it was a "retrograde development" is a meaningless comment: There had to be a beginning, and that was the point-contact transistor, not something else.

There is something else to say about the point-contact transistor: Its collector was "formed." To match the transistor output to the load, the collector was modified with a heating pulse from a charged capacitor or by transient heating from a variable ac source, or Variac. It was not unusual for "forming" to create a negative resistance behavior, the so-called hook collector. After the further ideas and contributions of various individuals, this discovery led directly to the pnpn switch. The version of this device that mattered, the first one constructed with silicon, was foreseen and guided into existence at Bell Labs by John Moll.[6] I was fortunate enough to be part of that work, which Bardeen kept up with, and the further work at General Electric that developed the pnpn switch into the silicon-controlled rectifier—the SCR, or thyristor—and then into the various shorted-emitter extensions such as the Triac. These inventions in turn led to symmetrical devices and ac operation.

When I left microwave-tube research to go to Bardeen's semiconductor laboratory in 1952, some of my colleagues and peers chuckled at what I was doing—choosing to leave tube research to work on semiconductors and transistors. At first we worked on point-contact transistors, with their limited capability of only micro- and milliwatts. Later, while on a recruiting trip from GE in 1960, I dropped off with John what was then a large SCR capable of handling hundreds of amperes and thousands of volts. John kept this in his desk till he died. He grinned when he showed it and mentioned its power rating. We both knew that the tiny, low-power point-contact transistor spawned the pnpn switch and, ultimately, perhaps today's most important high-power device, the SCR, which is capable of handling tens of megawatts.

John and I talked mostly about topical semiconductor problems. Within the last couple of years, however, after I ran into the comment about "retrograde development" and mentioned it to John, he and I got onto the subject of the point-contact transistor and its early development. John noted that the junction transistor took two years to build. It represented transistor technology's leaving the crystal surface (where the point-contact transistor operated), only to return much later to the surface with the development of diffused transistors, the technology that led directly to the integrated circuit. This was a very astute and important observation, a typical example of how quickly John saw the importance of key practical issues.

Much was learned from the point-contact transistor, including the advantages of constructing active regions from one reference, the surface. Because it was constructed as two closely spaced points on a single surface, the point-contact transistor was capable, as John pointed out to me, of much higher speeds—about 30 MHz—than early junction transistors. Until Robert N. Hall introduced alloying, which led immediately to the alloyed transistor, the only way to quickly turn a piece of semiconductor crystal into a transistor was to use point contacts.

Transistor oscillator and amplifier circuit

John never said to me explicitly that he was proud of the point-contact transistor, but he obviously was. And I think he talked to me about it because, apart from our long association, he knew that I appreciated the device's importance and what came from it. Also, as John knew, the point-contact transistor was the first type of transistor I had the opportunity to build in his laboratory before Hall, on the occasion of some Urbana lectures, described alloying to me.

In his own way, John was proud of the fact that the first transistor circuits employed point-contact devices. To the best of my knowledge, one of the first transistor circuits ever constructed was the two-transistor oscillator–amplifier shown on page 37. John told me that three of these point-contact transistor demonstration "boxes" were made in 1949: One was his, one was Brattain's, and one belonged to Bell Labs. My understanding from John was that only two individuals had these "boxes," and somehow Walter's got destroyed. John kept his in an office safe, but

every time he gave the semiconductor–transistor talk, he demonstrated the box. In fact, he would "key" the oscillator and play a tune—"How Dry I Am"—that could be heard on the center loudspeaker and could be amplified by switching in the second point-contact transistor. If we look in the plastic box, it is revealing to see that all the components are what existed in 1949 for vacuum tube circuits. Even the battery in the back of the box was a 45-volt B + supply for vacuum tubes.

On several occasions I suggested to John that his demonstration box, which he routinely brought to me for small-scale maintenance, should probably go to the Smithsonian. If a comment didn't interest John, he didn't reply or argue; he merely ignored it, as he did those times. In the spring of 1985, as he was leaving on a trip, he asked me to change the battery and take the box to the World Heritage Museum at the University of Illinois. Thus he insured that it was in the public domain but available to him for talks, demonstrations and so on. John Anderson, a friend of mine at GE in Schenectady, told me that at one such talk a couple of years ago to a radio history club near Rochester, New York, Bardeen was approached by representatives from the Smithsonian, who wanted his transistor box. On that occasion the oscillator transistor was damaged, apparently from poor airport baggage handling, but fortunately it still functioned. When I asked Bardeen about this event, he stated explicitly for the first time that he didn't want to give the Smithsonian his historic transistor circuit. In any case, Bardeen's demonstration circuit still exists, still operates and may be the world's oldest portable transistor circuit. This historic artifact was the first and may now be the only circuit of its type. Bardeen had the satisfaction of knowing it used point-contact transistors, not something else. There wasn't anything else.

The Bardeen legend

Bardeen was such a key figure in the beginning of transistor electronics that he would have become famous even if he had not been the source of other revolutionary developments such as superconductivity theory. Inevitably, various stories and legends develop around such a person. Maybe there was some truth in the way he was referred to, at least by some students, as "silent John" or "whispering John," and in the many stories that were told about his infallibility.

It is true that John spoke softly and at times became inaudible, particularly if he was in an extended discussion and deep in thought, or just tired. However, I learned very early, watching Brattain and Jane Bardeen, to speak in a strong voice with John: He would come into the discussion when he wanted, and loud enough to be heard. That was how Walter worked at the blackboard with John in Urbana in John's semiconductor laboratory from 1952 to 1954.

John was not the least bit "silent" in communicating in various ways with others. Besides his teaching, writing, committee work and academic seminars, he was a willing and frequent speaker and adviser to many groups, including ones from government and industry. (See George Pake's article on page 56.)

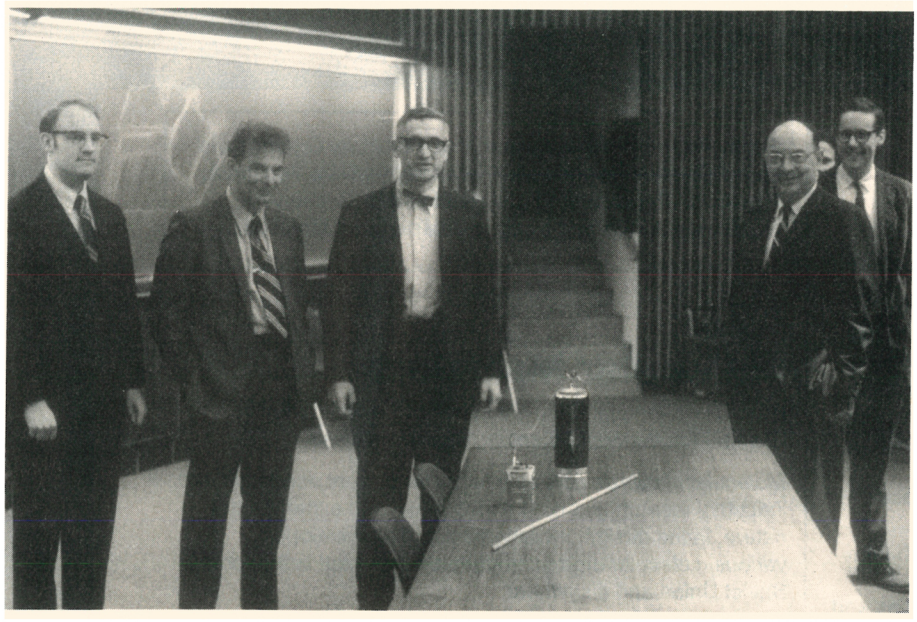
One reason John came to Urbana was the large electronics industry in Chicago, with which he thought he could interact. I remember a Chicago-area electronics industry seminar[7] in 1963 during which John used, among other material, some of my early GaAsP laser data[8] and pointed out to the attendees the significance of III–V light emitters—lasers and LEDs. Ten years later I gave, at John's urging, a talk at the same Chicago-area industry seminar, and the organizer, Paul Carroll, recalled that he had first heard of the coming of LEDs from Bardeen ten years earlier. The last paragraph of John's 1963 talk gives some idea of John's thinking:

> What applies to different countries also applies to different segments of our own industry. It is those who carry on advanced research programs on their own who are in best position to profit from new discoveries in science wherever they may occur. Illinois industry is backward in this respect; there are few outstanding industrial research laboratories, particularly in electronics. Even more dangerous for future growth in this area is that our best brains, our PhDs and the best of the BS graduates of our great engineering schools, go elsewhere where they feel that they have better professional opportunities. I do not think that the solution is to get more aerospace industry here. If we are to compete in the future with such advanced countries as West Germany and Japan, we need to get more of our best technical manpower thinking about problems of the civilian economy. For the future of our area, we certainly need to keep more of our best manpower in the Midwest. It is up to our industry to take the lead.

In part of my 1973 seminar talk I continued with some of these ideas.[9] They give us a sense of what he was aware of, and what he was telling others, 30 or more years ago.

Although we had many opportunities to talk in Urbana, John sometimes sent me a letter—from one university building to another—to clarify an issue, either for the record or to remove ambiguities. In 1987 a Japanese electronics magazine, *Nikkei Electronics*, published an article that included a description of how John assigned PhD problems. J. Robert Schrieffer was one of the two examples and I the other. A former student of mine and later of Karl Hess's, Hisashi Shichijo, now a colleague in Dallas, translated the article and asked me about the story. I wrote him a letter recalling what happened in my time in John's lab and describing, as I saw it, how Schrieffer came into the group. I sent John a copy of my letter to Shichijo, and John sent back a rather detailed letter correcting me. He pointed out that he took Schrieffer on as a theory student and brought him to our semiconductor project to give him an experimental background, not so that he would become part of the semiconductor effort as such or turn to experimental work. I had thought that John had brought Schrieffer in for semiconductor work and then switched him to superconductivity theory because Schrieffer did such a good job with the Boltzmann equation in dealing with surface transport, including his recognition of thin-layer quantum size effects. Actually, John had intended all along for Schrieffer to consider working on superconductivity theory.

Looking at this story, we could say, yes, indeed, John was infallible—just consider the BCS theory of superconductivity and how he started a young man in the direction of a Nobel Prize. It would be unfair to claim John was more than human. Of course, he made mistakes—not many, but some. Within the last three years, he commented to me that if any mistake was made



At Bardeen's semiconductor seminar, March 1971. Left to right: Robert D. Burnham, Zhores I. Alferov, Holonyak, Bardeen and Charles Duke. George Kleiman is partly visible between Bardeen and Duke. Bardeen organized the seminar series; at this session, Burnham spoke on InGaP lasers and LEDs. An InGaP LED operates at 77 K in the dewar on the table.

in our old semiconductor laboratory, it was failing to recognize and put more emphasis on the materials component of semiconductor device research. I am sure that Bardeen saw, as the years progressed, how vital materials work was in the advancement of semiconductor science and technology.

Bardeen earned his reputation for being infallible because of his overwhelming talent and great intuition, his profound understanding of quantum physics and his hard work and thinking about a problem before making his thoughts known. John wasn't quick to go public with half-baked ideas, and hence he did not make many open mistakes. When I came back to Urbana in September 1963 at his invitation, he wanted me to work on the silicon carbide laser, a "blue–green" laser that was then claimed to exist. I argued with John that it didn't exist and that what one of his former postdocs and others at Tyco Laboratories had shown him was misleading—in fact, wrong. I pointed out to him that in 1962 and 1963 I had looked at more "red" (visible) semiconductor lasers than any other person on Earth. Yet Tyco would not even show my technician, whom they were trying to hire, their blue–green lasers. Why should "blue–green" lasers look any different from "red" lasers? I told John that my red GaAsP lasers,[8] which operated at 77 K, required more cooling and more pulsed current than Hall's infrared GaAs lasers. That being the case, I asked him if he really believed Tyco's claim that SiC, an indirect-gap material, operated in the blue–green, not to mention at room temperature and continuously rather than pulsed. I told John I would believe him if he told me "different physics" was at issue. He knew at once this was not the case, shook his head and did not press the issue further. Shortly after John and I discussed the fictitious SiC laser, Hall presented incontrovertible evidence that it did not exist.[10]

Then was John really infallible? As far as all of us who regularly sought his advice were concerned, the answer is yes. John was deep, and he thought long and hard before he spoke. The trick was to come to John with questions within his domain of interest and thought—better yet, within an area of his work and experience. If I showed him some laboratory result of only mild interest to him, he would leave and return two or three weeks later to talk about other matters. If I showed him something of direct interest to him, he might return day after day with carefully worked-out material to help solve our problem. For example, I once showed him and Hess adjacent masked and nonmasked regions of a superlattice that we had converted from "red" in color to "intermixed and yellow" by low-temperature impurity diffusion.[11] I wanted him to see those layer disordering experiments because I remembered his in-depth knowledge of solid-state diffusion. (As a matter of fact, he had diffusion studies under way in our laboratory when I was his student in 1952–54; he knew that atom and impurity diffusion was developing as a method of making transistors.) As I expected, he immediately perceived facets of our disordering problem that we had missed. Even though John made mistakes, in the sense that really mattered to us, he was infallible.

* * *

I am grateful to R. T. Gladin for his expert advice and for duplication of photographs, Barbara L. Payne for manuscript preparation and John L. Moll for several conversations and for his perspective.

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