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A Case Study in Serendipity

Why Was the Transistor Invented at Bell Laboratories and Not at Purdue University?

by Ralph Bray

It is now almost 50 years since the invention of the point-contact transistor by John Bardeen and Walter Brattain in December 1947. The discovery was the culmination of a determined effort at Bell Laboratories initiated by William Shockley to develop a solid state amplifier (1-4). And it was the beginning of a technological revolution with far greater consequences than anyone could have envisioned at that time. Ironically, the invention was really the result of a serendipitous discovery, the unexpected consequence of a series of attempts to overcome failures of the field-effect transistor designed by Shockley.

Bardeen has stated that "advances made during the war at various laboratories in both material preparation and understanding of silicon and germanium were essential to the discovery of the transistor" (4). In particular, the prior work (1942-47) on germanium at Purdue University influenced the experiments at Bell Laboratories that led to the serendipitous discovery of the point-contact transistor. An interesting part of our story is that various transistor-related phenomena were unwittingly observed at Purdue quite early, but these were not understood until after the Bell Labs publications (5,6) announcing the discovery of the transistor in June 1948. Knowing about the status of the work at Purdue, Bardeen and Brattain were afraid (7) that the transistor would also be discovered there and that they might be beaten to the priority of publication during the six-month delay before their own publication—a delay imposed by secrecy requirements related to patent applications at Bell Laboratories.

My interest in this story is not only scholarly, but also has a personal basis. I joined the semiconductor rectifier project at Purdue University as a graduate student in physics in November 1943. I became intimately involved in the pre-transistor work. I did not fully appreciate the serendipitous nature of the transistor discovery until I attended a lecture by Bardeen on the history of the invention at an American Physical Society meeting in 1989. That lecture, in conjunction with the fears expressed by the Bell Labs group about the Purdue competition motivated me to investigate why the transistor was discovered at Bell Laboratories rather than at Purdue.

Pre-Transistor Work at Purdue University

Purdue's involvement in semiconductor research began in March 1942 under the direction and driving force of Professor Karl Lark-Horovitz, head of the physics department. His objective was to utilize the department's resources to support the national war effort with the objective of supplementing the radar technology effort at the Radiation Laboratory at M.I.T. by making improved crystal rectifiers. An immediate, specific objective was to minimize the problems with "burnout" that plagued the silicon diodes then in use (8).

> *"The discovery (of the point-contact transistor) was an accident, but Pasteur's statement that 'luck or chance favors the prepared mind' was exactly applicable."*

Lark-Horovitz organized a very small group of professors with diverse backgrounds from within the depleted physics staff, joined by about a dozen graduate students. Within this group there was no prior experience with the metallurgy of semiconductor crystals, the theory and properties of semiconductors, and the electronics of microwave radar. The decision was made early to concentrate on the semiconductor germanium. With excellent managerial skill, Lark-Horovitz organized three sub-groups to deal with the following problems:

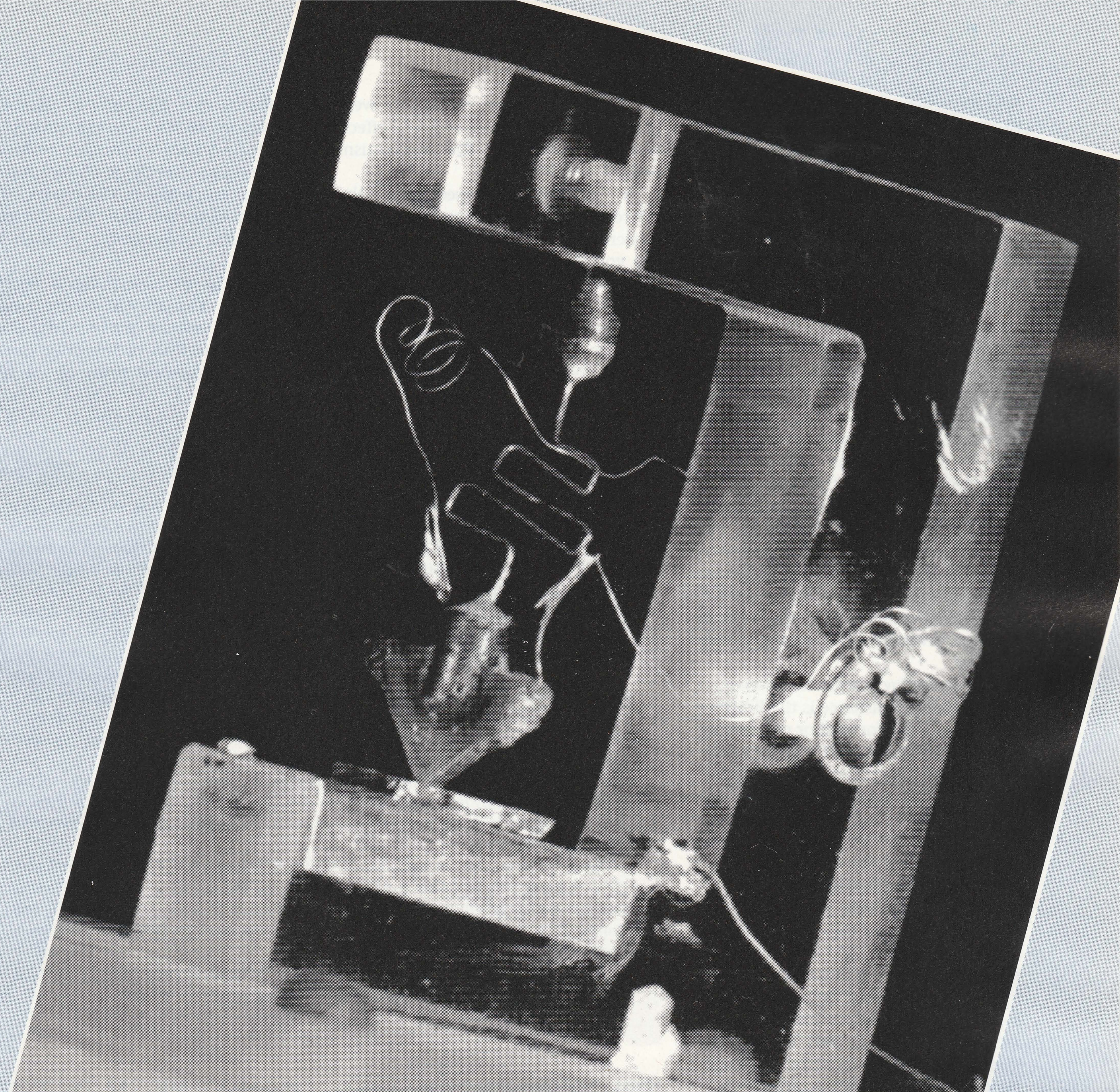
Metallurgy.—Because there were no commercial sources of germanium ingots, it was necessary to build a facility for purification and crystal growth with controlled doping with selected impurities (9). Although the ingots grown were polycrystalline and inhomogeneous by present standards, it was possible to cut selected samples, adequate for Hall and resistivity measurements and for making diodes.

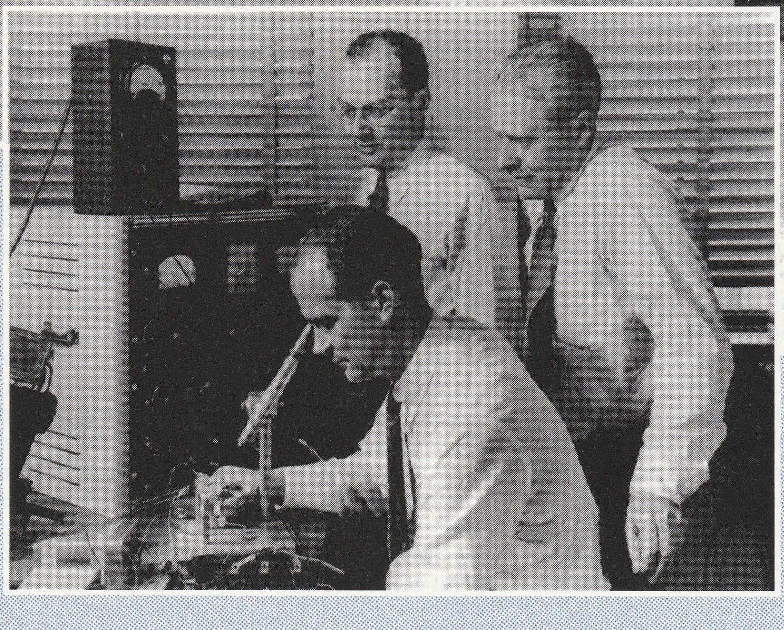
Characterization and analysis of germanium.—Measurements of the basic electrical and galvanomagnetic properties (resistivity, Hall effect and thermoelectric power) of the crystals served to characterize the ingots, and provide the feedback for improving the crystal growth techniques. The analysis of the measurements established for the first time the basic semiconductor parameters that made germanium the prototypical semiconducting material (10-12).

Development of the germanium high-back-voltage diodes.—The crowning technological achievement of the project was the manufacture of crystal diodes that could sustain high reverse voltages (>100 V), and thereby permitted them to avoid the "burnout" problems that plagued the earlier Si diodes (8). These high-back-voltage diodes were subsequently patented by Purdue (13) and became the basis for the first post-war, semiconductor industries. The factors in this success were the production of reasonably good germanium material, the development of successful surface chemical etching techniques and the discovery of the technique for "electrically forming" the tungsten whiskers to the germanium slabs by passing high currents in the reverse direction (8,10).

Along with the achievement of the basic objectives of the germanium project, a number of anomalous properties were encountered, some of which were relevant to the later discovery of the point-contact transistor.

The nature of the rectifying barrier.—According to the generally accepted





Above—The first transistor ever assembled; the year was 1947. It was called a point contact transistor because amplification or transistor action occurred when two pointed metal contacts were pressed onto the surface of the semiconductor material. The contacts are made of gold and the semiconductor is germanium. Public announcement of the transistor was made July 1, 1948 by Bell Laboratories. Right—In 1956, John Bardeen, Walter Brattain (standing, left to right) and William Shockley (seated) shared the Nobel Prize, the highest honor in science, for their discovery of the transistor effect.

Schottky theory, the rectification displayed at a metal-semiconductor contact was due to a potential barrier determined by the difference in the work functions of the metal and semiconductor. This was contradicted, however, by the experience that similar rectification was obtained for germanium diodes made with metals with different work functions. A critical experiment, designed by S. Benzer (14), clarified this anomaly. Benzer made an edge on edge, point contact between two similar pieces of chemically etched n-type germanium, for which there was, of course, no difference in work function. He found that the current-voltage characteristic consisted of what was the equivalent of two back-to-back rectifiers. The important conclusion was that there existed a natural potential barrier at the surface of n-type germanium, independent of any contact. Benzer attributed this to the presence of a p-type inversion layer on the n-type material.

The spreading resistance anomaly.—The spreading resistance is the limiting resistance in the forward or conducting direction of the diode. It is given by the slope of the current-voltage characteristic when the applied voltage is high enough (> 0.5 volts) to exceed the potential barrier at the contact. The spreading resistance derives its name from the geometrical spread of the current lines emanating from the metal point contact into the semiconductor slab. It provides a probe of the local resistivity near the point-contact, where most of the applied (forward) voltage in a diode is concentrated. My first assignment as a student was to use the spreading resistance to probe the homogeneity of the samples. Immediately, I found a large anomaly; the spreading resistance was generally much too low. It was lower by factors of 10 to 100 than the values that could be calculated from the overall bulk resistivity (15-17).

To determine whether the effect was peculiar to the point-contact geometry, I also measured the field dependence of the resistivity for bulk samples with rectangular cross section and with soldered, non-rectifying large area contacts. In this case, pulse measurements (a few microseconds in duration) were required to achieve sufficiently high fields (a few hundred volts/cm) without unduly heating the samples. Reduction of the resistance with applied field was found in all samples, both p- and n-type. The reduction was generally less than in the point-contact geometry, where the electric field near the contact is higher. It was obvious that we were dealing with some kind of a field effect, but the nature of the mechanism evaded us (15-18).

A mysterious aspect of the microsecond pulse measurements were hysteresis effects. During the onset of the voltage pulse there was a buildup time of several microseconds for the decrease in resistivity to take place, and a similar delay for the resistivity to return to normal as the voltage dropped (15-18). What I was observing, unwittingly, was conductivity modulation due to minority carrier injection into the bulk of the sample, produced by the applied electric field. Holes were injected into n-type material (or electrons into p-type material), with compensating increase in majority carriers to suppress space charge generation. This process could evidently occur in both the point-contact and large-area soldered contact configurations. The hysteresis effects were due to the initial injection and growth stage of minority carriers as they drifted into the sample, followed by the eventual recombination of the excess electron-hole pairs during the tail end of the voltage pulse. The roles ascribed here to minority carrier injection became apparent to me (17) only after the Bell Laboratories announcement of the discovery of the point-contact transistor in July 1948.

Rectification efficiency at microwave frequencies (8,10).—In the process of routinely testing the frequency dependence (from 60 cycles to 60 mc) of rectification efficiency of the diodes, H. J. Yearian observed that the efficiency diminished anomalously at high frequency.

Only in retrospect did it become clear that Yearian was seeing, unwittingly, the essence of a transistor effect, *i.e.,* the injection of minority carriers during the forward swing of the high frequency voltage, and their return to the contact during the reverse swing of the voltage. The point-contact diode was successively playing the roles of emitter and then collector, with these roles separated in time rather than in space as in the point-contact transistor.

A full account of the Purdue work (1942-46), including the anomalous results, was given in the final report (10) of the project which was widely circulated. In addition the results were presented at various meetings and discussed with numerous visitors including those from Bell and other industrial laboratories who wanted to get into the semiconductor arena. At no time did anyone suggest any explanation for the anomalous effects (except for the interest of Bardeen in the surface inversion layers, which related to his surface state work).

The Author

Ralph Bray is a Professor Emeritus of Physics at Purdue University. He received the Bachelor of Arts degree from Brooklyn College, and the Ph.D. in Physics from Purdue University. His research began serendipitously and unwittingly with transistor physics before the invention of the transistor. It was followed by studies of minority carrier injection, extraction and lifetime; hot carrier studies, particularly the determination of the distribution function; acoustoelectric amplification of phonons including domain motion and both Brillouin scattering and x-ray determination of the spectrum of the amplified phonons; Brillouin scattering determination of the interaction of surface plasmons with acoustic phonons; Raman scattering studies of electrons, acoustic and optical phonons; and non-equilibrium effects due to EL2 defects in GaAs.

After retirement in 1989, he pursued interests in a variety of subjects with varying intensity, from family and grandchildren to computers, photography, travel, and tennis to a fascination with the exploding advances in technology, cosmology, evolution, genetics, and the brain.

Some of his awards include: National Research Council Fellow (Delft, Holland, 1951-52); Guggenheim Fellow (Oxford, England, 1969-70); Fellow, American Physical Society; Visiting Scientist (Japan Society for Promotion of Science, 1977); and a von Humboldt Senior Scientist Award (Max Planck Institute for Solid State Research, Stuttgart Germany, 1984-85).

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The Bell Laboratories Transistor Story

My information on the details of the transistor work at Bell Laboratories is derived primarily from various articles written separately by Bardeen, Brattain, and Shockley, and from intensive interviews that they gave and that are in the archives of the Niels Bohr Library at the American Institute of Physics. These sources provide the full details of the path to the serendipitous discovery of the point-contact transistor.

There was some metallurgical and phenomenological research on semiconductors underway at Bell Laboratories even before the war, but such work had been kept under wraps (2). After the war, stimulated by the war-time progress on germanium and silicon, the semiconductor work began to be pursued much more vigorously. Most significantly, Shockley was empowered in 1945 to organize a semiconductor group to attempt to make a solid state switch, a gated amplifying device (1).

The Failure of Shockley's Design of the Field-Effect Transistor

Shockley (1-4) came up with a basic idea which ultimately became known as a Field-Effect Transistor (FET). (The term "transistor" was born later, after the discovery of the point-contact version.) The FET design consisted of a condenser formed by a thin slab of silicon with soldered end contacts and one face separated by a gap from a metal plate which acts as a gate. The electric field generated in the gap was supposed to provide control of the free carrier concentration near the free surface of the silicon, and thus modulate the conductivity of the slab. For effective modulation, the slab had to be very thin.

The first attempts to make an FET by Pearson and Shockley gave very weak effects, some 1500 times smaller than Shockley had estimated. Bardeen was asked to confirm Shockley's calculation, and to help explain the discrepancy. In March 1946, Bardeen postulated the existence of extra electron states on the free surface of the semiconductor (1-4, 20). If the energy levels of these states lay in the forbidden energy gap of the semiconductor, they could trap electrons from the bulk and immobilize them. The application of the electric field across the air gap would predominantly modulate the immobile electron concentration in these states, and "shield" the interior from the applied electric field. This would frustrate the attempt to modulate the conductivity of the semiconductor, and thus explain the failure of Shockley's proposed FET.

Furthermore, the trapping of free electrons from the conduction band on the surface states would create a potential barrier between the surface and the interior. The surface states could also trap electrons thermally excited from the valence band. This would create free, mobile "holes" in the valence band in a thin layer near the surface. This would constitute a conducting p-type "inversion layer" on the surface of the n-type semiconductor. Such a model explained the anomalous rectifier effects observed earlier at Purdue. Bardeen was quite aware of the latter work and it gave him confidence in the surface states model that he had proposed.

Attacking the Surface States Problem

Brattain and Bardeen teamed up in an attempt to control the surfaces states and their inhibition of the operation of a field-effect transistor. At one stage in the many discussions with their associates in the semiconductor group, it was suggested by Robert Gibney that an appropriate electrolyte, filling the spatial gap between the metal and the semiconductor, could produce a dipole layer at the surface and overcome the blocking action of the surface states. By employing this technique the blocking effects of the surface states were successfully overcome (1).

To improve the response, Bardeen made some crucial suggestions which had a profound influence. He suggested focusing attention on the naturally thin inversion layer, rather than the thinness of the whole sample. He recommended the use of a metal whisker as a probe of the modulation of the conductivity in the inversion layer. Finally, he recommended switching from silicon to germanium. In one of his interviews he states (21) that "it (germanium) makes good rectifying contact. We knew this from the work of the Purdue group. We had their germanium available, so it was easy to do the experiment. We knew from other experiments (Benzer's) that if you make contact between two pieces of germanium, you get about the same rectification characteristics as you would get with a metal point contact."

With these changes, considerable voltage as well as power amplification was observed. From the polarities of the metal plate and the probe it was deduced that the hole population in the p-type inversion layer was being modulated. However, the success was only partial. Because of the slow response of the electrolyte, amplification was obtained only at very low frequencies.

The Accidental Discovery

This failure led to the next scheme which was to replace the electrolyte by a solid oxide layer in the hope of obtaining a faster response. Brattain (22) describes the deposit of a small gold ring on top of the oxide layer to serve as the metal gate of the capacitor. A tungsten whisker was placed inside the hole of the ring to penetrate the oxide layer and make contact to the inversion layer. A large area base contact was soldered on the back of the germanium slab. A negative potential applied to the gold ring should, by induction, increase the hole concentration in the inversion layer and increase the current signal at the metal probe.

What happened next, according to Brattain (22), was an accident! In placing the metal whisker inside the ring, Brattain drew a spark from the gold ring. He states that he was disgusted with himself for ruining the experiment because the oxide layer might have been destroyed (if indeed it were present as a high resistance layer in the first place). Not having anything else to do until the original setup could be reproduced, he decided to carry on anyway and placed the whisker just outside the gold ring.

"The invention was really the result of a serendipitous discovery that would mark the beginning of a technological revolution with far greater consequences than anyone could have envisioned at that time."

Surprisingly, an effect was observed but one that was opposite in polarity to the expected one. They were looking for a negative potential on the gold ring to increase the hole population in the inversion layer. Instead, a positive potential on the ring produced an increase in current in the adjacent negatively biased whisker. Bardeen's first reaction to this surprising result was that instead of the capacitative induction of excess holes in the inversion layer by a negative potential on the gold spot, the latter was probably in direct contact with the inversion layer and was actually supplying holes to the p-type inversion layer by conduction. These "injected" holes were presumed to migrate through the inversion layer to the negatively biased whisker, now operating in the reverse, high resistance direction and thereby increasing its current.

Thereafter, the attempt to operate through an oxide layer was abandoned, and what came to be called a "point-contact transistor" was made by simply placing two whiskers very close together on the bare germanium surface, one serving as the emitter and the other as the collector of holes. In this way, a signal applied to the emitter contact generated both voltage and power gain at the nearby collector electrode. It was a device that was completely different in principle from the field-effect transistor proposed by Shockley, but served the originally desired function as a triode amplifier.

The Transistor Patent and the Nobel Prize

After the transistor discovery was announced, publicity releases from Bell Laboratories generally featured a posed picture of Shockley sitting in front of the manipulator which Brattain had built for the famous experiment, while Brattain and Bardeen were standing behind, just looking on. In an interview, Brattain said that orders came down the line, presumably because Shockley had contact with higher ups, "that no pictures were to be taken of Bardeen and me without Shockley's presence." The clear implication was to show that Shockley, as group leader, had played a prime role in the discovery. In fact, he had not participated in the invention, nor was his name included in the patent application. How could this have happened?

The story as described by Brattain (23) is that Shockley insisted on being included in the patent application by having the patent proposal combine both his field-effect-transistor concept (which indeed gave amplification but was too slow to be useful), along with the point-contact transistor. This was agreed upon. However, the legal department at Bell Laboratories was researching the patent files and found that the field-effect-transistor concept had already been patented earlier by a man named Lilienfeld. There is no evidence that the earlier patent had ever been reduced to practice. Nevertheless, this left Shockley out in the cold. The only patentable device was the point-contact transistor of Brattain and Bardeen, and so that is why only their names appear on the patent.

It is interesting that in 1956, the Nobel prize for the transistor was awarded to all three—Bardeen, Brattain and Shockley. According to Brattain, the management at Bell Laboratories threatened not to support the nomination of Bardeen and Brattain unless they agreed to include Shockley.

Shockley's Reaction and Other Consequences

Shockley says (1) that the invention, which was formally disclosed to upper management on December 23, 1947, was a magnificent Christmas present to the laboratory. He states, "I shared in the rejoicing. My elation was tempered by not being one of the inventors. I experienced some frustration that... my personal efforts had not resulted in a significant invention of my own." This frustration motivated him in the month from December 24, 1947 to January 24, 1948 to formulate the concept of the n-p-n junction transistor. It was in conjunction with this device that Shockley first became aware of the role of minority carrier injection from the emitter contact. The technology for making a junction transistor in the n-p-n configuration was not realized for some time, and the first junction transistor was not constructed until 1950. It behaved just as Shockley had predicted. Eventually, the bipolar transistors of the junction type completely replaced those of the point-contact configuration.

It is ironic that it was Shockley himself who was at least partly responsible for the long delay in making the first junction transistors. Shockley thought that it was sufficient to work with polycrystalline ingots to make transistors. According to Brattain, he discouraged Gordon Teal's attempts to grow single crystal ingots, and William Pfann's attempt to make homogeneous material by the zone melting process. These metallurgical advances were just what was needed to make Shockley's proposed junction transistors feasible.

Another ironic note is that Shockley's field-effect-transistor concept was finally resuscitated some 15 years later at Fairchild Semiconductor, where it was discovered that good, stable oxides could be formed on silicon. The MOSFET (metal-oxide-semiconductor-field-effect transistor) was born there. This was exceedingly important because this structure was much more compatible with the technology of forming integrated circuits on chips, where thousands (and later millions) of transistors could be formed on one chip.

The Minority Carrier Injection Concept

There has been some contention over the priority for proposing the concept of minority carrier injection, which is the essential mechanism in the operation of the transistor. Bardeen has stated that in interpreting the initial observation of the transistor "the way the holes flowed from the emitter to the collector was uncertain... the idea of the inversion layer was very important in our thinking of the field-effect experiments, and of the modulation of the conductance of the minority carriers in the inversion layer. And we probably had too much in our minds about the inversion layer which would provide a channel for holes going from the emitter to the collector. The question is how important that aspect was compared to the flow of holes through the bulk, which Shockley meant by the term "minority carrier injection." It appears to me that Bardeen was cautiously waiting for additional experiments to determine what was the path of the excess holes (24).

When Bardeen was asked about how the spreading resistance anomalies observed at Purdue affected his thinking, he states (21) that when he first learned about the Purdue experiments, the explanation became obvious that conductivity was being increased in the vicinity of the emitter contact, the point contact, by the emission of holes, which increased the number of carriers. "And this made us somewhat concerned that maybe the Purdue group would also think of the transistor, and so, (we were) anxious to publish as rapidly as possible, to get priority on the discovery."

In contrast with the uncertainty of Bardeen and Brattain, Shockley, working with the junction transistor concept in mind, was able to make the immediate jump to the idea of minority carrier injection into the bulk. He was quite aggressive in his claim to have been the first to recognize the central role of minority carrier injection into the bulk. He said (1) that he arrived at this concept in his burst of activity just after the invention of the point-contact transistor in December 1947.

Shockley may be correct in his claim that he was the first to articulate the concept of minority carrier injection, but since he was apparently out of touch with his colleagues during that period of intense preoccupation, he perhaps was not aware of what others in the laboratory were thinking. There is some evidence that the idea might well have been "in the air."

I was not aware of the Bell Labs work until I read the Bardeen and Brattain papers in July 1948. I immediately concluded then from my own experiments that there had to be injection of minority carriers into the bulk material. We had found conductivity modulation both from point contacts and from large area soldered contacts and this could only be compatible with bulk injection. However, by the time I was aware of the Bell Labs results, it was too late to contribute because the problem was already being solved by others in a series of experiments at Bell Labs.

Why Was the Transistor Discovered at Bell Laboratories and Not at Purdue?

Bardeen and Brattain had been looking for a triode amplifier. Although the point-contact transistor was not what they had contemplated, its functional behavior was just what they wanted. This permitted them to immediately recognize what chance had wrought. Although the discovery was an accident, Pasteur's statement that "luck or chance favors the prepared mind," was exactly applicable. Furthermore, Bardeen's focus on the surface inversion layer provided an immediate basis for him to suggest a model, *i.e.,* the transport of holes through the inversion layer connecting the emitter and collector. Even though it was soon supplanted by the mechanism of minority carrier injection into the bulk, it did provide the rationale for appreciating what was happening and for proceeding with the development.

While the anomalies observed at Purdue were related to aspects of point-contact transistor behavior, they were not of the form to make the idea of a transistor itself immediately obvious. It would have required some flash of insight to achieve that. Had the mechanism of minority carrier injection, and its similarity to the production of excess electron-hole pairs by optical excitation been recognized, the possibility of a transistor might have been more apparent. Even without that mechanism, we might have stumbled onto a transistor if we had sought to determine the spatial influence of the modulation of the spreading resistance on an adjacent probe. The format of a point-contact transistor, whether planned or accidental, was never achieved except in the indirect fashion of Yearian's frequency-dependence experiments. However, the main factor remains that we were not looking for such a device and Brattain and Bardeen were, and some serendipitous event that would have permitted us to stumble onto it simply did not occur.

It should also be noted that the environment at Bell Labs was very conducive to discovery. Due to lack of space, Bardeen, Brattain, and Pearson shared one office which promoted strong interaction and frequent informal discussion between experimentalists and theoreticians. It seems that Bardeen was frequently present at Brattain's side in the laboratory during all the crucial experiments. There were frequent group meetings and lunches at which physicists and chemists informally exchanged ideas. This cultural environment was absent at Purdue. I do not remember any informal brainstorming sessions where we talked about the various anomalies. Although we had group meetings where we had to report results, there was not the atmosphere of carefree give and take between equal, mature scientists.

The situation was quite different at Purdue in other ways. The early work was driven by the exigencies of the wartime situation. Everyone was responsible to Lark-Horovitz. There was relatively little free and open group interaction. While there was occasional talk of the possibility of a triode, there was never any inclination or leadership to promote it. After the war, the group quickly fell apart, with professors going back to their original interests, some students staying on to finish their dissertations, and other leaving Purdue. In the crucial period of the year preceding the invention of the transistor, there was barely a group left to interact with at Purdue.

The success of the work at Purdue and the invention of the transistor made it easy to obtain research funding from government agencies after the war. It supported a regrowth of the semiconductor group which became the biggest one in the physics department at that time. Similar developments soon occurred at other universities and in various industrial research laboratories. No one at the time realized the potential of the discovery and the forms into which it would evolve and what role it would play in technology and society in general in the next 50 years. ■

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