



A HISTORY OF SEMICONDUCTOR RESEARCH

by

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ABSTRACT

A review of the experimental and theoretical activities leading to the 1948 discovery of the transistor by Bardeen and Brattain. The point is stressed that the significance of the invention of the point-contact transistor is that it represents the complete formulation of the theory which explains all semiconductor behavior. Brief mention of the early applications and dissemination of information concerning these devices.

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INTRODUCTION

After a scientist or an engineer has made an innovation, he presents it to the world in its finished form as an obvious thing. The theory and the mechanics behind it are, indeed, obvious to him. On the other hand, those to whom it is presented are likely to be perplexed by its previously unexplored and unexplained intricacies. This is not paradoxical, however, since the inventor himself was undoubtedly equally as perplexed before concentrated research, study, and probably initial failure led to the final, successful act of invention.

This is one of the major obstacles to technical innovation. As yet, no simple method of invention has been devised. Perhaps careful study of the process of invention will eventually yield insights into the character of innovation itself. One can only hope that if the elements of invention are properly dissected and carefully studied, a pattern will emerge which may be applicable to future, unrelated attempts at innovation.

The process of innovation may be clearly seen in the events leading to the invention of the transistor. The earliest work in this area, beginning with Faraday's

discovery of the inverse temperature-resistance characteristic existing in silver sulfide, was largely empirical. By 1885, the three other major properties of semiconductors (the rectification of alternating current, the generation of a photo voltage, and the increase of conductivity in the presence of light) had been observed, although they remained unexplained.

The rise of quantum mechanics led A. H. Wilson to propose an explanation of these phenomena in 1931. Few workers recognized the full impact of Wilson's theory, which received little attention when first announced. World War II was responsible for a vast increase in the applications of semiconductors, although a complete explanation of their properties was still lacking at war's end.

Due largely to the efforts of William Shockley, a program was initiated at the Bell Telephone Laboratories to investigate further the properties of semiconductors. This program had as its goal the complete understanding of semiconductor behavior, in the hope that such knowledge would lead to commercially applicable products.

It was in the course of this fundamental investigation that Bardeen and Brattain discovered the transistor effect and the point-contact transistor which is illustrated in Figure 1. With the information obtained in these experiments, Shockley was able to revise his theories in sufficient detail to predict accurately the properties of the junction transistor two years before its actual fabrication.

Thus the significance of this invention is twofold; it represents both the successful completion of the theory, and a useful application derived from the theory.

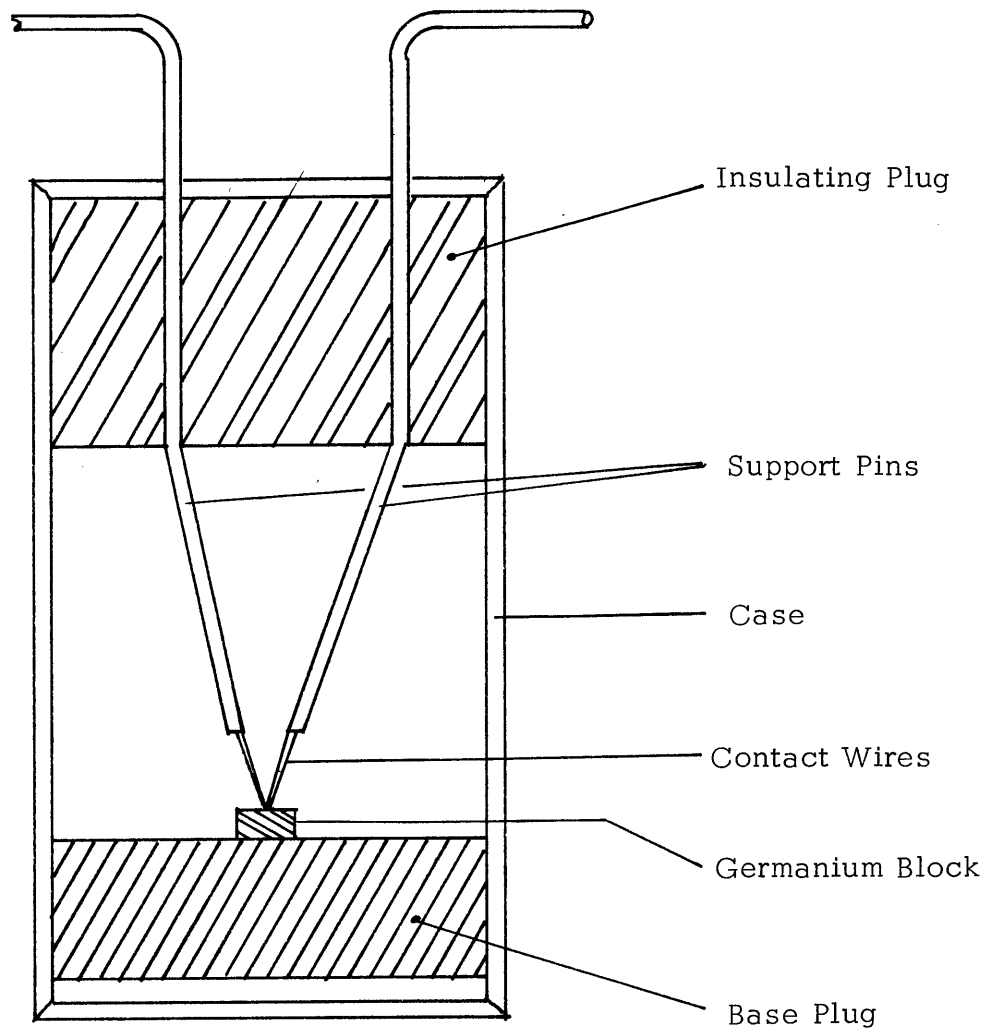


Figure 1

Bell Laboratories' Type A Transistor

EMPIRICAL DEVELOPMENTS PRIOR TO 1940

The class of materials which we know today as semiconductors was first discovered by Michael Faraday in 1833 when he noted that the resistance of silver sulfide decreased with increasing temperature,¹ a result entirely out of keeping with the data on all other substances. Faraday could offer no explanation for this phenomenon, and in fact none of the early observations of semiconduction could be explained with any of the (then) current theories of electromagnetism.

Becquerel, known primarily for his early work in radioactivity, observed in 1839 that a photovoltage was generated by shining a light on the surface of an electrode immersed in an electrolyte, and thus added a second fact to the small store of knowledge of semiconduction. In 1873, W. Smith found that the resistance of selenium was reduced by shining a light upon its surface, thus adding photo-conduction to the list of unexplained properties.²

¹G. L. Pearson and W. H. Brattain, "History of Semiconductor Research," Proc. IRE, XLIII (Dec. , 1955), 1794.

²Smith, W. , "The Action of Light on Selenium," J. Soc. Telegraph Engineers, Vol. 2, #1 (1873), 31-33.

Braun, in 1874, discovered a fourth quality of semi-conductors, that of rectification or nonlinearity. He saw that contacts between certain metallic sulfides, such as galena, would allow a current to pass in one direction, but not in the reverse direction.¹ C. E. Fritts, continuing in this direction with selenium, produced the first dry rectifier in 1883.² We see then, that by 1885 four of the fundamental properties of semiconductors had been empirically observed, although in different materials, and that no consistent theory to explain these phenomena had been presented.

Semiconductors and their peculiar properties continued to exist as scientific curiosities until about 1910, when their potential as radio wave detectors was established by several workers, among them J. C. Bose, H. H. C. Dunwoody, and G. W. Pierce.^{3,4} Thus was

¹F. Braun, "Uber die Stromleitung durch Schwefel Mettalle," *Anal. Phys. und Chem.*, Vol. 153, #4, (1874) 556-563.

²C. E. Fritts, "New Form of Selenium Cell," *Amer. Science*, Vol. 26 (Dec., 1883), 465-472.

³Pearson and Brattain, p. 1794.

⁴G. W. Pierce, "Crystal Rect. for Electrical Oscillators," *Phys. Rev.* (Vol. 25, July 1907), 31-60, (Vol. 29, Nov. 1909), 478-484.

invented the famous "cat's whisker," which kept a generation glued to their radio sets, in search of that "elusive spot." Work on semiconductor development might have begun in earnest at this time, had it not been for the invention of the vacuum tube, which performed capably at the required frequencies with far less effort than the familiar crystal, which subsequently was placed on the shelf.

In the twenties, the demand for knowledge about semiconductors increased, as the photoconductive property of these materials was commercially exploited for photo-cells and their rectification property was used for nonlinear elements in electronic circuits.¹ McEachron, at General Electric, discovered that this nonlinear property made semiconductors good lightning arresters, thus contributing another commercial use of the materials.²

Those who had deserted the crystal detector after the invention of the vacuum tube returned to the fold in the late thirties, as interest grew in radio waves of

¹L. O. Grondahl and P. H. Geiger, "A New Electronic Rectifier," Trans. AIEE, Vol. 46 (Feb., 1927), 357-366.

²K. B. McEachron, "Thyrite, a New Material for Lightning Arrestors," General Electric Review XXIII (Feb. 1930), 92.

short wavelengths and tubes were found to be incapable of handling the high frequencies involved in short wave detection. The crystals required for this purpose had to be of a purity not attainable with the current technology, and efforts were directed at developing new refining techniques. R. S. Ohl formed a group at the Bell Telephone Laboratories which studied the problem of silicon materials and developed the necessary technology to produce not only pure silicon, but also silicon crystals with specified impurities necessary for special applications, notably n- and p-types silicon. Scaff and Theuerer, working with Ohl, produced a crystal which was n-type at one end, and p-type at the other, thus forming the first p-n junction. This was to take on great importance in the future.¹

While work in the United States was centered about the use of semiconductor detectors, in Germany two physicists were pursuing a more elusive goal, the construction of a solid-state amplifier, an analog of the

¹J. H. Scaff, H. C. Theuerer, and E. E. Schumacher, "P-type and n-type Silicon and the Formation of the Photo-voltaic Barrier in Silicon Ingots," Trans. Amer. Ins. of Mining & Metallurg. Eng., Vol. 185 (June, 1949), 383-388.

vacuum tube triode. R. Hilsch and R. W. Pohl reasoned that if the diode rectifier performed the function of a solid-state rectifier, then it should be possible to make a crystal triode which would function in the same manner as its glass-encased counterpart. Since the triode used a grid placed between its filament and plate in order to amplify a current, then similarly, a control grid placed within the crystal rectifier would be able to use a small current to modulate a larger one, thus achieving power amplification. Unfortunately, in the common semiconductors, the effects leading to rectification took place in a space approximately one-tenthousandth of a centimeter wide, and it was obviously impossible to insert a grid in this volume. In crystals of potassium bromide, however, ionic effects similar to those in "regular" semiconductors occurred in a space of about one cm. Hilsch and Pohl succeeded in inserting a grid in such a crystal in 1938, as shown in Figure 2, and achieved power amplification by a factor of twenty. Since these effects were ionic in nature, this amplifier worked on an entirely different principle from that of our modern transistor; consequently, the frequency response of this device was limited to less than one cycle per second, making it impractical for

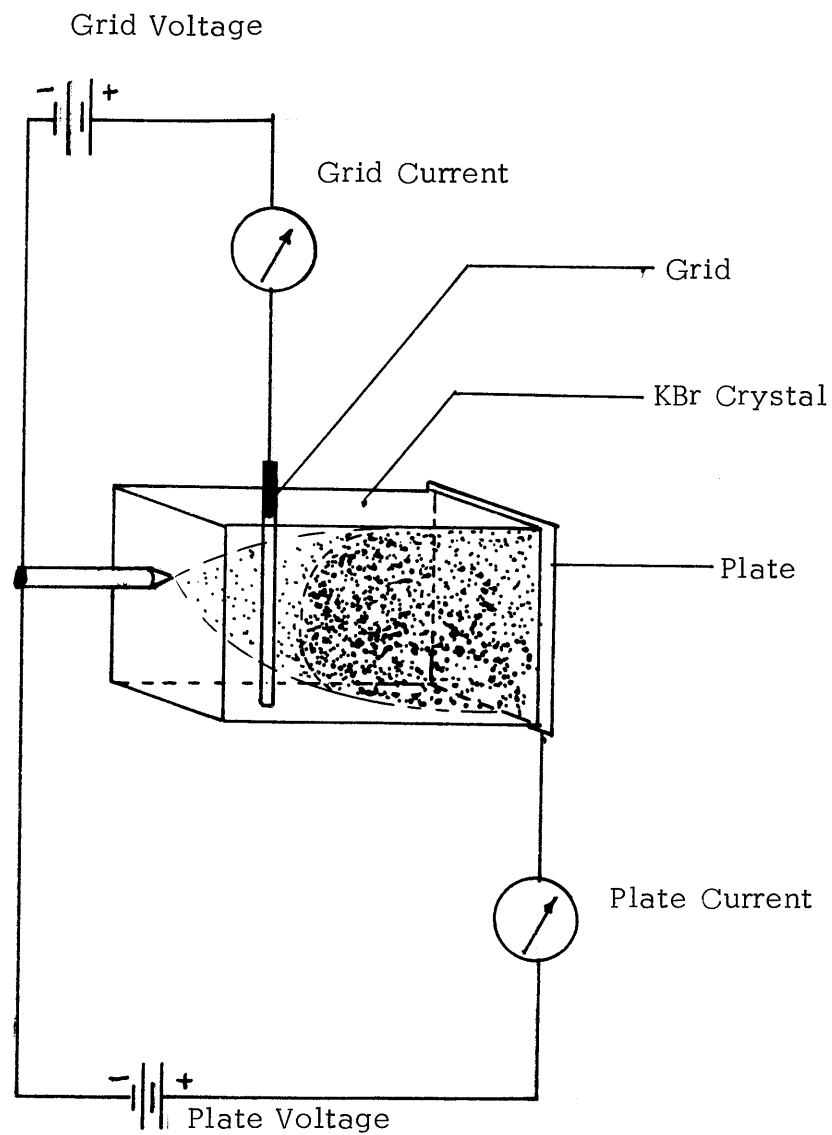


Figure 2

The Experiment of Hilsch and Pohl

(Shaded areas represent ionized fields within the crystal)

any electronic devices.¹ Nevertheless, this development was a foreshadowing of things to come.

¹R. Hilsch and R. W. Pohl, "Steuerung von Elektronenstromen mit einem Dreielektrodenkristall und ein Modell einer Sperrschicht," Z. für Phys., CXI (Dec., 1938), 399-408.

THEORETICAL DEVELOPMENTS PRIOR TO 1940

As noted earlier, the first discoveries concerning semiconductors were presented as curiosities, and therefore no theoretical explanations were offered. With the birth of atomic theory in the early part of the century, attempts were finally made to explain these phenomena of semiconduction. It was proposed that different mechanisms were responsible for different aspects of the behavior.

Photoconductivity and the decrease in resistance with temperature were thought to be properties of the semiconductor alone (body properties), with the light and/or heat providing the energy required to free electrons, thus increasing conductivity. Photovoltage and nonlinear properties of both the semiconductor and its metal contacts, or the junction of two semiconductors; the phenomena were thought to occur at the interface of the two.¹ Thus the problem of explaining semiconductor behavior was split into two parts, one involving surface phenomena, and the other body properties. This separation has persisted until the present, and as will be seen later, it served well in the development of the modern transistor by

¹Pearson and Brattain, p. 1795.

William Shockley.

At each stage of its development, semiconductor theory could progress no further than the current atomic theory. The discovery of the Hall effect in 1879 is a case in point. Hall found that electrons flowing in a metal could be deflected by a magnetic field perpendicular to the direction of current flow. It was soon demonstrated that the charge carriers in metals were negative, i. e. , electrons.¹ For some semiconductors it was determined that the charge carriers were positive, which was confusing (modern theory postulates the existence of electron deficits, or holes, which may be considered as positive electrons; this was, of course, unknown at the time).

Further Hall measurements indicated that the number of carriers in a semiconductor was substantially less than those in a metal, and that these carriers were relatively freer to move about within the material than the electrons in a metal. Thus the conductivity of semiconductors was shown to be a function of the same parameters (number of carriers and mobility) as the conductivity of normal conductors. It was further shown that

¹E. H. Hall, "On a New Action of the Magnet on Electric Currents," Amer. J. Math., Vol. 2 (Nov., 1879), 287-291.

as the temperature of the material was increased, the number of available carriers grew rapidly, while their freedom to move about decreased slowly; overall, the conductivity increased with increasing temperature. One aspect of semiconductor behavior had been explained.^{1,2}

The birth of quantum mechanics proved to be a godsend to the investigators of semiconduction. In 1927 Davisson and Germer at Bell Labs demonstrated the wave nature of an electron beam,³ and soon thereafter Sommerfeld offered a quantum mechanical explanation of metallic conduction. The breakthrough came in 1931, when A. H. Wilson presented a quantum theory of semiconductors, which postulated the existence of energy levels in the atoms of the solid. At low temperatures, electrons would reside in the lowest possible energy levels, and as the

¹W. Vogt, "Elektrisches und Optisches Verhalten von Halbleitern IX," *Anal. der Physik*, Vol. 7 (July, 1933), 501-542.

²W. Schottky and F. Waibel, "Die Elektronenleitung des Kupperoxyduls," *Physikalische Zeitschrift*, Vol. 34 (Dec. 1, 1933), 858-864.

³F. W. Van Name, Jr., Modern Physics, (Englewood Cliffs, N. J., 1962), p. 174.

temperature is raised, some electrons become thermally excited, and attain the energy necessary to jump to higher levels, and are free to conduct a current. The theory also predicted that the gaps left by departed electrons would act as positive charge carriers, or holes, thus explaining the results of the Hall effect. Wilson's model explains the effects observed when impurities are inserted into the semiconductor crystal: adding material with an electron deficiency creates a hole which is free to move, while adding a substance with an electron excess provides a highly mobile electron.¹ Pearson and Brattain point out that it took about fifteen years for the light shed by the theory to dawn, and further note that one of the major problems "arose from the fact that it was much simpler to consider a semiconductor with one type of defect or the other, rather than both at the same time."²

An explanation of rectification based on the

¹A. H. Wilson, "The Theory of Electronic Semiconductors," Proc. Roy. Soc. London, Vol. A133 (Oct., 1931), 458-491.

²Pearson and Brattain, p. 1797.

quantum theory was proposed in 1939 by Mott, who argued that a potential barrier existed between the surface of a semiconductor and a metal or other semiconductor. Electrons would be able to traverse this barrier in only one direction, hence rectification.¹ Thus, by 1940 theoretical explanations of semiconductor behavior had been formulated, and with only a few exceptions, the models conformed to the observed behavior. With the improved metallurgical technology developed by Ohl and the theory developed by Wilson, all that was required to improve the state of the art was a vital need for improved semiconductors. World War II was to provide such a need.

¹N. F. Mott, "The Theory of Crystal Rectifiers," Proc. Roy. Soc. Lon., CLXXI (May, 1939), 27-38.

DEVELOPMENTS DURING THE WAR

The development of microwave radar during World War II required the use of high frequency wave detectors. The use of vacuum tubes proved to be inadequate, as the noise level of these devices increased rapidly with the frequency at which they were operating. Thus the National Defense Research Committee formed a high priority program to develop semiconductors capable of operating at the extremely high frequencies of 3,000 to 30,000 megaHertz/sec. Such devices would prove impracticable unless their quality was uniform and their reliability could be assured. In addition to developing such devices, then, it was necessary to develop methods and equipment to measure performance in the laboratory and to measure the quality of production devices. It was further recognized that many aspects of semiconductor behavior were incompletely understood, and that fundamental research in such areas as point-contact rectification was needed.

A large part of the NDRC's program was carried out at the M. I. T. Radiation Laboratory between 1940

and 1946. This work was, of course, confidential, but after the War H. C. Torrey and C. A. Whitmer summarized the work done in the semiconductor program in Crystal Rectifiers. Due largely to the demands of war, the research conducted during the period emphasized improved applications rather than improved understanding, and the state of the art improved vastly. Seitz, in a program at duPont, developed a method for the production of extremely pure silicon, to which desired impurities could be added, providing conductivity and rectifying capability of a uniformity not previously attainable. Rectifiers using this silicon performed far better than those made by the same techniques but with ordinary commercial silicon.¹ The discovery that boron was highly effective as an impurity agent was a second major advance in the technology, while the development of special purpose crystal devices was the third major contribution of the NDRC program.

It would be unfair to groups at both Purdue University and the University of Pennsylvania to close this section without reporting that much of the fundamental

¹H. C. Torrey and C. A. Whitmer, Crystal Rectifiers, (New York, 1948), p. 9.

research carried out under NDRC contracts was done by these organizations; Dupont should also be given credit for the development of manufacturing techniques which made the uses of semiconductor devices practical.¹

¹J. Bardeen, "Research Leading to Point-Contact Transistor," *Science*, CIVI (July 19, 1957), 105.

SEMICONDUCTOR RESEARCH AT BELL LABS

At the close of World War II, the Bell Telephone Laboratories initiated a program of intensive fundamental research in semiconductor physics, which culminated in the invention of the point-contact transistor by Bardeen and Brattain in 1948. The reasons for Bell Labs' commitment to semiconductor research are significant both in the context of the history of semiconductors and in the philosophy of industrial research and technological innovation.

The decision to engage in semiconductor work was made by two men: M. J. Kelly, Bell Labs' Director of Research; and William Shockley, an M. I. T. Ph. D. working in the basic research section of the Laboratories. Their decision reflected a good understanding of both future needs and present abilities. Kelly saw that the growth of the communications industry required that new devices be developed. The limitations of the present-day technology, especially vacuum tubes, seemed insurmountable. Tubes were inefficient, generated vast amounts of heat, and had a relatively short lifetime. The

alternative to tubes, mechanical relays, were far too slow for the rapid switching that would be required of future telephone systems. Kelly sought a device which would combine the reliability of relays with the speed of tubes, but would lack the inherent disadvantages of the tube. Shockley was familiar with the developments in semiconductor technology and theory, and believed that a more perfect understanding of these devices might lead to advances of the type sought by Kelly. Neither had any idea of what form such a device might take, if any, but only the belief that the area looked promising. Thus the decision to pursue the area was made, and an Authorization for Work was drawn up (see Appendix I).¹

The group which began this research under the direction of Shockley consisted of Walter Brattain, who was concerned primarily with surface states and rectification, G. L. Pearson, who interested himself with bulk properties, and John Bardeen, who was concerned with both areas. Later R. B. Gibney, a physical chemist, and H. R. Moore, a circuit analyst, were added to

¹J. A. Morton, "From Research to Technology," International Science and Technology (May, 1964), 87.

the group.¹ This group was able to draw upon the earlier work done at Bell Labs by Ohl, Scaff and Theuerer in the materials area.

The aim of this program was to develop as complete an understanding of the various semiconductor effects as possible; thus it was a sharp contrast to the NDRC program during the war, and complemented this study by attempting to explain theoretically what had been discovered empirically. The theory with which it started was essentially the same as the one completed in the thirties, consisting of Wilson's quantum explanations and Mott's theory of contact rectification. Quantum mechanical analytical techniques had been improved by exercise during the war, and the materials with which they could experiment were far better controlled, owing to the success of the war research. There were indications that the theory was misunderstood and/or that materials refining techniques were still imperfect, revealed in the inability to predict properly the behavior of point-contact rectifiers.

Two approaches to electronic control were explored.

¹Bardeen, p. 105.

The first, analogous to the vacuum tube triode, proved unworkable in semiconductors, since the "space-charge" layer in which the electronic effects took place was of microscopic size, thus prohibiting the insertion of a "control grid." Hilsch and Pohl had already demonstrated that the space-charge layer of the alkali-halides was of sufficient dimensions to permit such an insertion, but their experiment had shown that only a limited frequency response was possible with this technique. This led Shockley to formulate his "field-effect" theory.

Shockley argued that if a semiconductor were placed in an electric field, charges could be induced in the slab which would act as current carriers. By varying the field, the conductance would vary; thus amplification would be possible.¹ This theory totally relied upon electrons as carriers, and neglected the holes whose existence had been demonstrated by the Hall effect and explained in Wilson's theory. This technique was attempted, as illustrated in Figure 3. The results were completely negative; no such effect could be detected.

¹ Bardeen, p. 106.

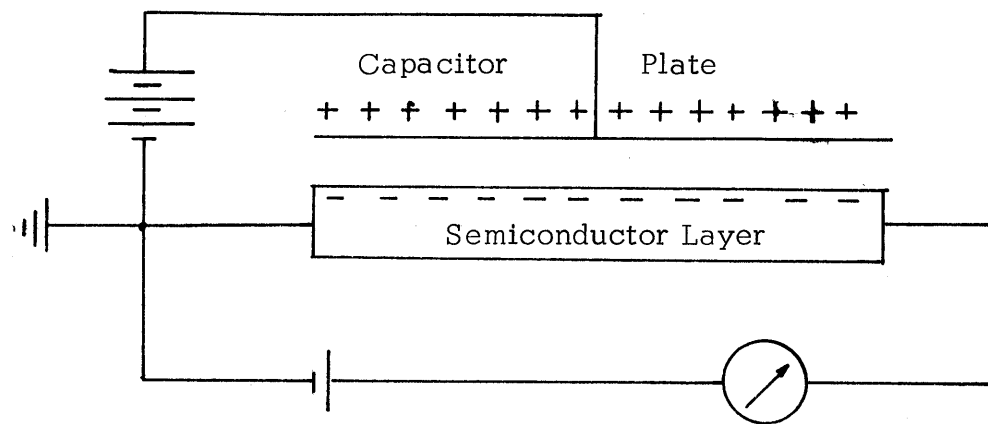


Figure 3

Diagram of Shockley's idea for a field-effect transistor using a n-type semiconductor with no surface states.

Since Wilson's theory failed to explain the lack of success of Shockley's experiment, modifications of the theory were obviously in order. Bardeen proposed that there existed special "surface states" whose behavior differed from that of the body's interior.¹ Such states would shield the body from any external fields. Thus, the failure of Shockley's experiments was explained. These surface states also served to explain rectification by postulating that the rectifying barrier was actually at the surface, before contact was made.² Shockley demonstrated that if surface states did exist, then the surface potential would be affected by shining a light on it; an experiment corroborated this result. Gibney performed measurements of the surface potential when immersed in an electrolyte and found great variations in this potential with varying voltages applied across the solution; this indicated that the strong field produced by the ions in solution at the surface could penetrate through

¹Bardeen, "Surface States and Rectification at a Metal to Semiconductor Contact," *Phy. Rev.*, Vol. 71 (May, 1947), 717-727.

²*Ibid.*

the surface barrier.¹

Bardeen and Brattain felt that they could induce a field inside the semiconductor if they used a point contact at the surface, surrounded by, but insulated from a charged electrolyte, which would serve to weaken the surface states.² An experiment to test this theory was performed (using p-type silicon, i. e. , an excess of holes) and it was discovered that a small current in the electrolyte would allow a larger current to flow from the semiconductor to the point contact, thus achieving current (and power) amplification. (See Figure 4.) Thus, the transistor effect was first observed.³

The use of an electrolyte in this situation served to limit the frequency response of the transistor, and means were sought to eliminate it. In one attempt, a

¹Bardeen, Research, p. 110.

²Ibid.

³Ibid.

spot of gold was evaporated on a germanium surface, and a point contact placed nearby the spot. As shown in Figure 5, a high resistance contact was desired, but none could be obtained, so the experiment continued with a low resistance gold spot-germanium contact, "to see what effects could be obtained."¹ With the gold spot biased in one direction, and the point-contact biased in the reverse, some voltage amplification was obtained. More importantly, however, the experiment suggested that holes were flowing from the gold spot, to the germanium block, and then to the point contact, and out of the block, thus increasing the output current. It was then found that the use of the gold spot was unnecessary, and transistor action would occur with two points contacts placed in close proximity (0.05 cm.) on the germanium block.² This device provided voltage and power amplification, and the point-contact transistor shown in Figure 6 had been invented.

In analyzing the behavior of the transistor, Bardeen and Brattain found that a significant part was

¹Bardeen, p. 111.

²Ibid.

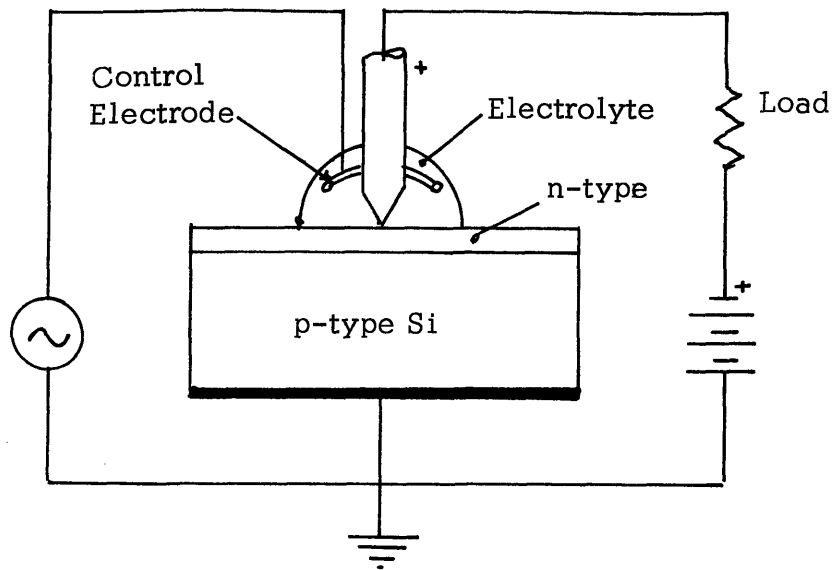


Figure 4

Experimental Set-up using a drop of electrolyte

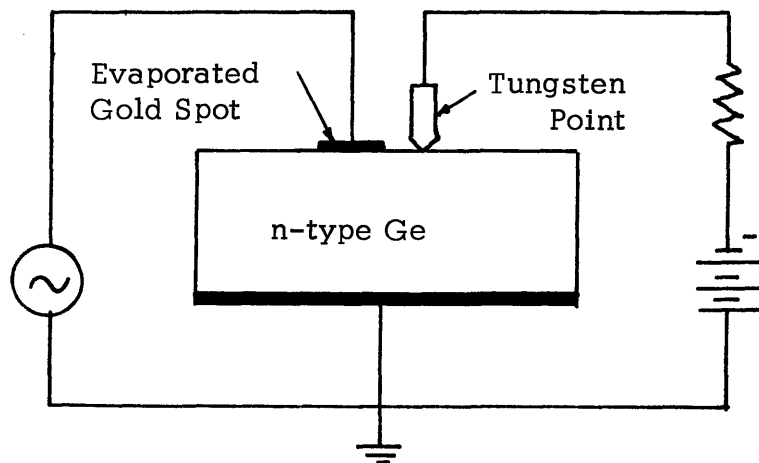


Figure 5

Electrolyte replaced by a gold spot

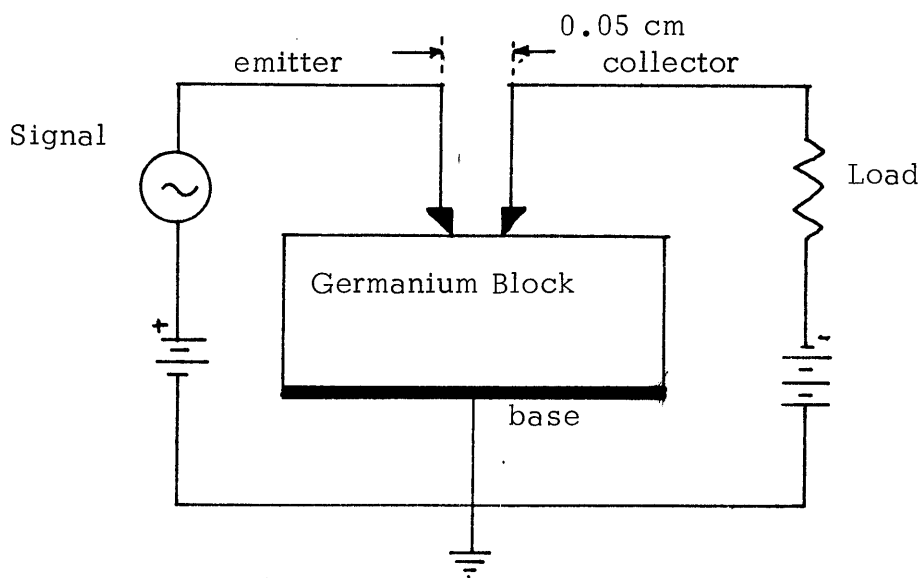


Figure 6

The Point-Contact Transistor

Holes introduced at the emitter flow to the collector

played by holes, which are the minority carriers in N-type germanium. "If this fact had been recognized earlier, the transistor might have come sooner," Bardeen noted in his Nobel Prize acceptance speech.¹ It should be noted that the point contact transistor functions entirely differently from the first of Shockley's proposals; perhaps the most interesting aspect of early transistor development is the feedback which occurred between theory and implementation. The first implementation demonstrated that Wilson's theory was incomplete; the theory was modified in light of the experiment and a new test was performed, leading to limited empirical success. After experimentally improving the device, the theory was once again analyzed, and revised to explain the observed behavior; at this point the theory proved to be complete.

The ultimate test of any theory is its ability to predict future experimental results. That Shockley's theory was complete was demonstrated when in 1949, on the basis of the theory, he was able to predict the characteristics of a p-n junction transistor,² although

¹Bardeen, p. 111.

²W. Shockley, Electrons and Holes in Semiconductors, (New York, 1950), p. 92.

the actual development of such a device did not occur until 1951. At that time it conformed nicely with the theoretical behavior predicted. Thus the actual development of the point-contact transistor is in itself less significant than what it represented -- the completion of a theory to explain the behavior of electrons and holes in solid-state devices.

IMPROVEMENTS IN TRANSISTOR TECHNOLOGY

Although the invention of the point-contact transistor represented a culmination of sorts of the efforts of Shockley, Bardeen and Brattain, it was merely one step more in Bell Lab's attempt to replace the vacuum tube with a solid state counterpart. Jack Morton, the manager given responsibility for converting the transistor from an experimental plaything to a commercial product, notes that three major problems existed at the time:¹

"Units intended to be alike varied considerably from each other -- the reproducibility was bad.

In an uncomfortably large fraction of the exploratory devices, the properties changed suddenly and inexplicably with time and temperature, whereas other units exhibited extremely stable characteristics with regard to time -- the reliability was poor.

It was difficult to use the theory and then existing undeveloped technology to develop and design devices to a varied range of electrical characteristics needed for different circuit functions. Performance characteristics were limited with respect to gain, noise figure, frequency range, and power -- the designability was poor. "

¹J. A. Morton, "Present Status of Transistor Development," Proc. IRE, XL (Nov. , 1952), 1314.

All of these problems were related to the physical nature of the early point-contact transistor, which involved a mechanical contact to produce the transistor action. The invention of the junction transistor in 1950 and the development of techniques to grow single crystals containing p-n barriers greatly contributed to the solution of these problems, as did the various improvements in production methods of refining and adding impurities in required amounts. By 1952, Morton could (and did) say, "With respect to reproducibility and interchangeability, transistors now under development appear to be the equal of commercial vacuum tubes."¹

A significant improvement in the materials aspect of transistor technology was made in 1952, when W. G. Pfann of Bell Labs developed the technique of zone refining. Pfann noted that in germanium, impurities tend to segregate into the molten portion of a solidifying ingot. By repeatedly passing molten zones through an ingot, it was possible to attain crystals with less than one impure atom for each ten billion germanium atoms, which is prob-

¹Morton, "Present Status," p. 1326.

ably the highest purity ever attained in any substance.¹

The adaptation of techniques developed for germanium crystals to other semiconducting substances occurred in the following years: in 1954, Teal, working at Texas Instruments, announced the first grown junction silicon transistor, capable of handling higher frequencies than its germanium counterpart. In 1955, methods of introducing impurities by diffusion had been perfected, again increasing the frequency response and power handling capabilities of transistors. Frosh and Derrick at Bell Laboratories, developed production methods which made possible the fabrication of hundreds of devices on a single slice of material, which could then be cut up into individual components. In 1958, Kilby developed the integrated circuit, by applying the techniques of Frosh and Derrick, but stopping short of separating the individual components on the silicon wafer.²

It is the integrated circuit, better known as the IC,

¹W. G. Pfann, "Principles of Zone Refining," Trans. Amer. Ins. of Mining and Metallurg. Eng., Vol. 194 (July, 1952), 747-753.

²Arthur D. Little, Inc., The Sergeant, Polaris, and Minuteman Missile Systems (U), (Camb., 1965), pp. 77ff.

which is making possibly today the micro-miniaturization found in our mammoth communications and computation systems. The chronology of these events is given in Appendix 2.

None of these improvements, however, is as significant as the point-contact transistor of Shockley, Bardeen and Brattain, which first established that the principles revealed by Wilson's analysis of semiconductors could find practical applications. One can imagine that the invention of the wheel was an analogous situation; once the principle of rolling had proved practical, rounder wheels, smoother wheels, pneumatic tires, tubeless tires, snow tires and rain tires all seemed trivial developments in comparison.

THE GROWTH OF TRANSISTOR APPLICATIONS

Considered in the light of its great significance, the public send-off of the transistor was quiet indeed. The July 1, 1948 edition of The New York Times noted on page 46 that John Bardeen and Walter Brattain, working at the Bell Telephone Laboratories, had succeeded in developing a solid-state electronic device that could perform the function of a vacuum tube. Brief announcements of a similar nature appeared in technical journals.

Shortly after the initial development of the transistor, Bell Labs organized a group to explore applications. Progress was, of course, limited at first because of the small quantity and questionable quality of the first production transistors. But by 1951 enough experience had been gained to merit a symposium on transistors at Bell Labs. For a modest fee, representatives of industry, government and schools were tutored in the theory, properties and applications of the various devices. Among the devices exhibited were

assorted computer logic elements (bit registers, shift registers, binary adders, and a "not and" gate), transistorized switching circuits, and various transistor amplifiers.¹

The transistor fulfilled a definite need for the military, which was engaged at the time in the Korean conflict. Shortly after the announcement of the junction transistor in 1951, the military Research and Development Board realized that it could not wait for a firm demonstration of military usefulness before it began to construct facilities for the production of the devices, and \$13 million was appropriated for pilot plants before anyone knew exactly how these products would be used.² This faith in the transistor was noted by Ralph Brown, the research vice president of Bell Labs, when he

¹ Bell Telephone Laboratories, The Transistor (New York, 1951).

² F. Bello, "The Year of the Transistor," Fortune (Mar., 1953), 129.

said:¹

"The transistor development indicates the depth and power of present-day technology. The vast build-up and research being put into the transistor, in advance of any commercial return, reflects industry's faith that scientists and engineers know what they are talking about. "

A symposium on transistors held by R. C. A. in late 1951 attracted almost as much attention as the earlier Bell symposia. One of the featured exhibits, and the most popular one, was a television set with completely transistorized circuitry.²

An indication of public interest in the transistor may be seen in the listings under "semiconductors" to be found in the Reader's Guide to Periodical Literature. In 1948, there were three entries; in 1949 a dozen; 1950 -- two dozen; 1952 -- a few dozen, and 1952 the same. In 1953 the listing grew to a column, and the following year it took up a page. The rest is history, as the country went transistor-mad. As yet, there is no change in view.

¹R. Brown, "Transistor as an Industrial Research Episode," *Scientific Monthly*, Vol. 180 (Jan., 1955), 45.

²Bello, p. 162.

SUMMARY

The history of the modern semiconductor dates to 1833, when Faraday first noted that certain materials did not conform to the direct relationship between temperature and resistance which had been assumed universal. By 1885, the three other properties, photo-voltage, photo-conduction, and nonlinearity, which set semiconductors apart from metals and insulators, had also been experimentally observed. This strange behavior was explained theoretically by A. H. Wilson in 1931, although the full impact of Wilson's theory passed by many workers, and thus the successful exploitation of semiconductor properties was delayed several years.

World War II created a demand for semiconducting crystals, and thus prompted new research into methods of refining these materials. This improved technology led Shockley and his colleagues at Bell Telephone Laboratories to seek further understanding of these substances, in the hope that they might fill a need for electronic control devices. Shockley's

research demonstrated new properties of semiconductors, which Bardeen explained by the addition of surface states to Wilson's theory. Using the revised theory, the transistor was developed; analysis of the device's behavior revealed that it was working for different reasons than were theorized. The theory was once again modified, this time with success, as it allowed Shockley to calculate theoretically the characteristics of still unconstructed transistor devices.

When it was possible to fabricate such devices, because of improvements in materials technology, their observed characteristics did in fact agree with what had been predicted. It was the completion of this theory which is the truly significant result of the research conducted at Bell Labs.

APPENDIX I

Text of Project Description for Shockley's Work at Bell Laboratories¹

SUBJECT Solid State Physics -- the Fundamental Investigation of Conductors, Semiconductors Dielectrics, Insulators, Piezoelectric and Magnetic Materials.

STATEMENT Communication apparatus is dependent upon these materials for most of its functional properties. The research carried out under this case has as its purpose the obtaining of new knowledge that can be used in the development of completely new and improved components and apparatus elements of communications systems.

We have carried on research in all of these areas in the past. Large improvements in existing types of apparatus and completely new types have resulted. Thermistors, varistors and piezoelectric network elements are typical examples of new types. The quantum physics approach to structure of matter has brought about greatly increased understanding of solid state phenomena. The modern conception of the constitution of solids that has resulted indicates that there are great possibilities of producing new and useful properties by finding physical and chemical methods of controlling the arrangement and behavior of the atoms and electrons which compose solids.

¹Morton, "From Research," p. 91.

APPENDIX II

Chronology of Semiconductor Research

<u>Year</u>	<u>Discovery</u>	<u>Individual</u>
1833	Inverse Temp. -Resist. relation	Faraday
1873	Selenium photoconductivity	Smith
1876	Selenium photocell	Adams
1879	Hall Effect	Hall
1883	Selenium rectifier	Fritts
1931	Semiconductor Quantum theory	Wilson
1938	Silicon crystal detector	Ohl
1938	Crystal Triode	Hilsch, Pohl
1939	Rectifier Theories	Mott
1945	Bell labs starts investigation	Shockley
1948	Point-contact transistor	Bardeen, Brattain
1949	Prediction of Junction Transistor	Shockley
1949	Single Crystal growing	Teal
1951	Grown Junction transistor	Teal
1952	Silicon junction diode	Pearson
1953	Surface barrier devices	Bradley
1954	Silicon Rectifier	-----

<u>Year</u>	<u>Discovery</u>	<u>Individual</u>
1954	Silicon transistor	Teal
1956	Diffusion transistor	Fuller
1957	Esaki diode	Esaki
1958	Integrated circuits	Kilby
1958	Planar techniques	Hoerni

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