BY STEVEN J. BABBERT, W6THU

THE BIRTH OF THE TRANSISTOR

Most of us know that the transistor was discovered at Bell Telephone Laboratories around the middle of the 20th century. It is also common knowledge that the solid-state revolution which followed rendered the vacuum tube obsolete in nearly every electronics application. What many people don't realize is that some of the effects that make the transistor possible were being studied as early as the 1800s.

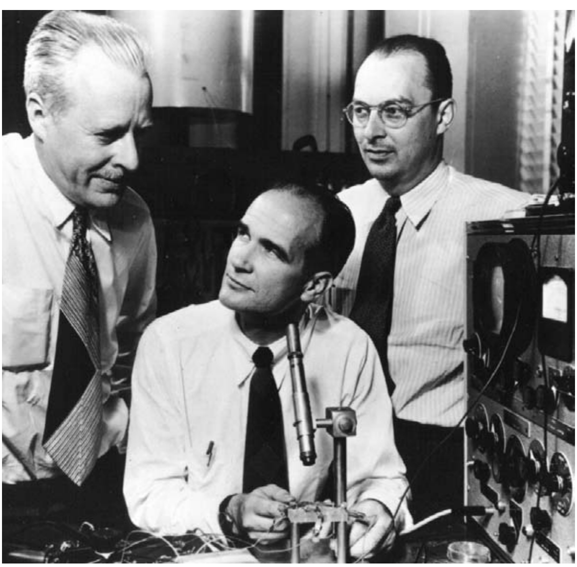
Early Discoveries

Some of the fundamental properties of semiconductors (i.e. the characteristics that set them apart from metals and insulators) were being investigated before the turn of the century. The negative temperature coefficient, characterized by an increase in resistance when temperature is decreased, was observed in silver sulfide by Michael Faraday as early as 1833. In general, all semiconductors and electrolyte solutions have a negative temperature coefficient while that of pure metals is positive.

Alexandre E. Becquerel discovered the photovoltaic effect in 1839. He observed a voltage of about 0.1 volt between a pair of dissimilar metal electrodes immersed in an electrolyte when exposed to light. In 1876, W.G. Adams and R.E. Day observed the same effect in selenium, a solid which would later be used in semiconductor devices. This material was also used in the first known study of photoconductivity made by Willoughby Smith in 1873. He found that small rods of selenium became better conductors when exposed to light.

Rectification, perhaps one of the most important semiconductor effects, was discovered by German Physicist Karl F. Braun in 1874. He observed that when sharpened wires were brought into contact with galena (lead sulfide) crystals and pyrites, an essentially one-way current conduction characteristic resulted. This type of device eventually became known as a point-contact diode.

Another important discovery, the Hall effect, was made in 1879 by E. H. Hall. He noticed that a small voltage is developed across a current-carrying conductor in the presence of an external magnetic field. The Hall Effect was later found to be very pronounced in semiconductors. Though these ef-



From left: Brattain, Shockley and Bardeen recreate first successful transistor test. Photo courtesy Lucent Technologies.

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fects were little more than curiosities at first, they would become important factors in the development of semiconductor theory.

Wireless Technology Evolves

Wireless technology, though still in its infancy, was evolving rapidly in the early 1900s. Radiotelegraphy, the original form of wireless communication involving the transmission and reception of damped-wave telegraph signals, was giving way to radiotelephony which involves audio signals impressed on a continuous wave. The damped-wave signals which were created by a spark discharge into an antenna circuit could be received by using one of various forms of crude non-rectifying detectors. Radiotelephony signals, on the other hand, were amplitude modulated and therefore required rectifying detectors.

In 1901 Braun had developed a crystal detector based on his earlier discovery of point-contact rectification. His detector consisted of a piece of psilomelane (manganese oxide) with an adjustable wire contact which was referred to as a cat's whisker. Though initially used for radio telegraphy, it would also work for radiotelephony because it was a rectifier.

Similar devices were being devised and patented in the U.S. In 1906 H. C. Dunwoody and G. W. Pickard patented the use of carborundum and silicon respectively for use as detectors. These crystal or "cat's whisker" detectors can be considered the first commercially successful solid-state devices.

In 1904 English physicist and engineer Sir John Ambrose Fleming introduced the "thermionic valve" or vacuum tube diode which was also used as a wireless detector. It was more complicated than the cat's whisker since it required a filament voltage and a partial vacuum but it was more stable. In 1906 American experimenter Lee DeForest added a third element (the control grid) transforming the diode into a triode.

As a detector of radio signals the triode didn't offer much advantage over the diode; However, within a few years the control-grid turned out to be the key to unlocking the full potential of the vacuum tube. In 1912 Major Edwin Armstrong, often regarded as the most important American electronics inventor of all time, discovered regeneration, a form of very high-gain amplification. By applying positive feedback from the plate to the grid of a triode, Armstrong found that signals which had been barely audible could now be heard loud and clear. Soon, the triode was being used ln numerous electronic circuits including oscillators and transmitters.

The Crystal Triode

The analogy between the cat's whisker detector and the vacuum diode was an obvious one and ultimately led investigators to search for a way to interpose a third element into the semiconductor diode. Unfortunately, the theory and technology required for such an undertaking did not yet exist. The principles of point-contact rectification itself were not understood. On the other hand, the vacuum tube was relatively easy to modify and its fundamentals were fairly well understood. Consequently, scientific interest turned largely towards vacuum tube technology.

Because crystal detectors were cheaper than tubes and crystal sets were simpler and required no batteries, many wireless enthusiasts continued to use them either in home-brew or kit form. By around 1910, silicon, galena and carborundum were being used. Mass-produced tube sets didn't overtake crystal sets until about 1925. During that period some enterprising individuals experimented with "crystal triodes" of various designs. Some apparently did provide "gain" or amplification.

Some devices were very simple, consisting of a chunk of silicon with three contacts made at various points using various methods. These experimental "transistors" were connected into a receiver circuit in much the same way as transistors are today. Like all amplifiers, they required a supply voltage. In some cases, amplification could be increased by using a vise to apply a transverse pressure to the crystal. Many crystals were shattered in an attempt to turn up the volume.

Other devices were more sophisticated; some even bore a resemblance to the transistor as we know it today. J. E. Lilienfeld, for example, patented a device utilizing cuprous sulfide in l925. Lilienfeld himself was not able to correctly explain the theory behind his invention! But apparently it worked and was used in several amplifier stages of a receiver which was shown on the patent. However, the Lilienfeld patent did not result in the development of any practical technology.

By the mid l920s solid-state devices were also finding use in non-radio applications. Copper oxide and selenium rectifiers were being used to permit the operation of d.c. apparatus from commercial a.c. power. In these units, rectification took place at the boundary between the layers of two dissimilar materials. Photocells were also being produced using selenium and cuprous oxide. As in the case of the point-contact rectifier, the effects involved in these devices were not yet understood, but their use stimulated scientific investigation.

The Quantum Revolution

Quantum theory was introduced by Max Planck in 1901 and, after being advanced by many scientists, led to the quantum mechanical theory of semiconductors which was developed largely between 1926 and 1931. Quantum mechanics deals with the behavior of matter and light on the atomic and subatomic scale, and attempts to describe and account for the properties of atoms and their constituent particles. By the beginning of the 1930s, with the help of this powerful tool, an understanding of the various semiconductor effects was emerging.

Experiments had revealed that conductivity was dependent on the density of charge carriers and that this density increases with temperature in semiconductors. It was also learned that current was carried by positive charge carriers (originally called "deficit electrons," they are now called holes) as well as by negative electrons. Band theory was used by A.H. Wilson to study the processes by which conduction occurs in solids. The concept of "acceptor and donor" states associated with the intentional "doping" (admixture of impurities in trace amounts) of otherwise pure semiconductors was introduced. The resulting semiconductor types came to be known as "deficit" and "excess" and would eventually become the building blocks of nearly all solid-state devices.

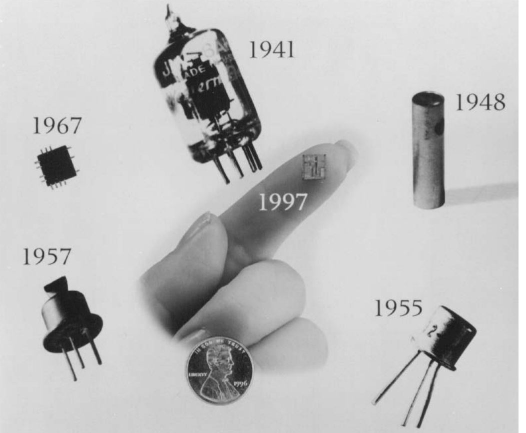
The photo effect was explained by I. I. Frenkle of Russia. He theorized that light energy created pairs of electrons and holes which diffused away from each other at different rates. With this, most of the effects observed in the 1800s were at least partially understood. An understanding of rectification was still over the horizon.

One question that researchers had been trying to answer for years was whether rectification was a bulk or an interface property of metal-to-semiconductor contacts. Two men involved with the evolution of rectifier theory were Sir Nevill Mott of England and Walter Schottky of Germany. Both men working independently of one another concluded that rectification takes place in a thin electrical barrier that formed at the junction of a metal contact and a semiconductor. Schottky referred to this an "inversion region." These findings would play an important role in future experiments during which the transistor was discovered.

A Russian, B. Davidov, suggested in 1938 that in metal-to-semiconductor contacts, there is a change from excess to deficit at the interface and that this is where rectification took place. He also recognized the importance of minority carriers (holes or electrons depending on their relative numbers) in rectification and in producing photovoltage. Minority carriers would later be shown to be an essential component of transistor action.

Research Becomes Organized

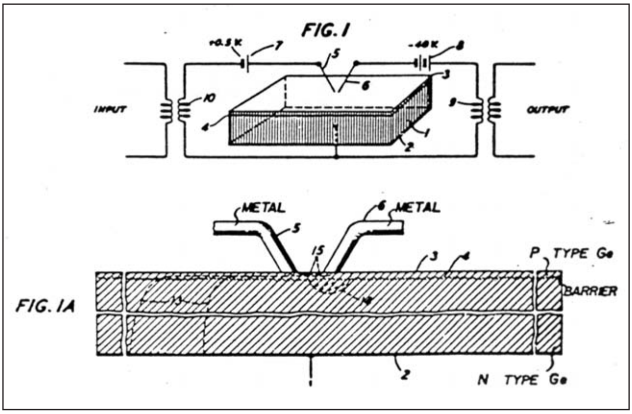
One researcher, G. C. Southworth of Bell Labs, began his study of silicon by obtaining several old cat's whisker detectors from a New York radio market. Germanium point-contact rectifiers had been manufactured since around 1925 and were very sensitive, but silicon was known to be more stable. The promise shown by these crude detectors prompted researchers to



Clockwise, from 1941: vacuum tube used in telephone communications; first transistor; transistor which replaced vacuum tube in telephone communications; diffused base high-frequency broadband amplifier; microchip for producing telephone set touch tones. On fingertip: digital signal processor containing as many as 5 million transistors. Photo courtesy Lucent Technologies.

search for ways to increase the purity of silicon and germanium. To this end, teams of physicists, chemists and metallurgists were formed.

Toward the beginning of World War II simultaneous developments were taking place secretly in various countries. Americans and Germans made considerable progress in purifying silicon and germanium. They learned how to custom-make both excess and deficit types, or n-type and p-type as they became known at Bell Laboratories. J. H. Scaff and H. C. Theuerer of Bell produced a melt that was p-type at one end and n-type at the other, with a sharp boundary in between. The p-n junction so formed was investigated by R. S. Ohl of Bell Labs and found to be an excellent rectifier. It would also produce a strong photovoltage when exposed to light. Before long, p-n junction diodes were being manufactured.



Details from original transistor patent show test circuitry and construction.

During World War II research became more highly organized. Under the leadership of M.I.T. Radiation Laboratory, various industrial and academic institutions, including Bell and Purdue, were brought together to study semiconductors for radar (microwave) applications. This resulted in a mixing of scientists and ideas and opened a line of communications between industry and university. Scientists at Purdue focused on the fundamental electrical properties of germanium. The progress they made in the preparation of purer materials and fabrication of detectors created an early lead enjoyed by germanium over silicon.

The Semiconductor Group

The wartime semiconductor developments had set the stage for the invention of the transistor. In July of 1945 an "authorization for work" was issued at Bell Labs for the purpose of initiating research to be used in the development of new and improved components and apparatus for communications systems. This document formally set in motion the Bell Labs solid-state research program and, within a few months, a subgroup known as the Semiconductor Group. It was from this inter-disciplinary group that the transistor would emerge.

A key member of this group was Walter H. Brattain, who joined Bell Labs in 1929 as a research physicist after receiving his doctorate from Minnesota. He was assigned to a branch of vacuum tube research dealing with surface properties in metals. By 1931 he had been put to the task of studying the phenomenon of rectification in the semiconductor copper oxide.

Another key member of the semiconductor group was William Shockley. He joined Bell Labs in 1936 as a theoretical physicist just after having been awarded a Ph.D. in physics at M.I.T. He too was put to work on vacuum tubes though he was more interested In a different field—the behavior of electrons in solids. He was seeking answers to three basic questions. (1) Physically, what is a semiconductor? (2) How does its physical nature produce its observed properties? and (3) How does the fabrication and processing of the material affect its physical nature?

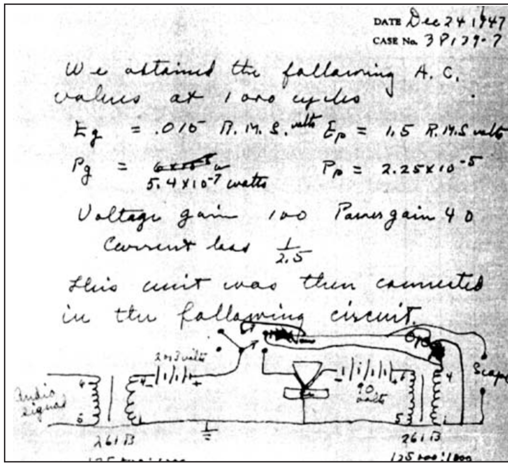
At Cambridge in the mid-1930s, Shockley met a young theoretical physicist named John Bardeen. Bardeen had earned a B.S. degree in electrical engineering at the University of Wisconsin in 1928. In 1945 he joined Brattain and Shockley at Bell partly at Shockley's request. One of Bardeen's fields of expertise was solid-state physics.

An Alternative to the Vacuum Tube Was Needed

The semiconductor group was aware that there was a real need at Bell for an alternative to the vacuum tube. As early as 1936 it had become apparent that the mechanical switches used in telephone exchanges would have to be replaced with electronic ones if the long-term needs of the system were going to be met. The so-called crossbar system, though state-of-the-art at the time, would seriously limit any increase in complexity. Vacuum tubes held little promise because of their inherent weaknesses and limited life. A radically different type of device was needed.

With this in mind, in l946 the group decided to focus on silicon and germanium and later to include a study of both the surface and bulk properties. Shockley theorized that it should be possible to modulate the resistance of a thin layer of semiconductor by applying a strong electric field. When experiments failed to give the expected results, Bardeen entered the picture in an attempt to figure out why.

Bardeen had studied conduction in solids extensively. Expanding on the earlier work of Schottky and Mott, he developed a "theory of surface states." This refined theory suggested that, in Shockley's experiment, surplus electrons became trapped at the surface of the semiconductor and acted to cancel the electric field needed to produce a change in resistance. The new theory was the basis for the group's decision to investigate surface phenomena.



Page from Brattain's laboratory notebook records transistor test carried out on Christmas Eve 1947.

Many experiments were carried out by Bardeen, Shockley, Brattain and others at Bell Labs to test the surface-state theory. Some of the experiments involved putting more than one point-contact on the surface of a semiconductor slab. It was during just such a procedure that the transistor effect was first observed by Brattain and Bardeen on December 23rd, 1947.

The Prototype

The two men decided that amplification might be possible with a dual point-contact structure provided that the distance between the contacts was less than two mils. This posed a problem since the wires themselves were five mils in diameter and it would be difficult to keep them from touching. To avoid using wires altogether, Brattain got a technical aide to fashion a triangular piece of polystyrene, slightly flattened at its apex. He than cemented a strip of gold foil along two edges with its center at the apex. The foil was cut in two at the apex so that there was a narrow gap between the two foil contacts. The device was mounted on a spring which held the contacts against a base of anodized germanium. One foil contact became the emitter and the other, the collector.

The device was connected into an amplifier circuit similar to that of a vacuum triode in a grounded-grid configuration. Brattain used his voice as an audio test signal and devised a means to switch the device in or out of circuit as needed. He found that when in-circuit, the level of the audio signal was greater. This could be heard on a speaker and seen on an oscilloscope. The following day a working oscillator was built which provided further proof that amplification was taking place. This led to a busy Christmas at Bell Labs and triggered an explosive increase in related research.

The name transistor was suggested by Bell physicist J.R. Pierce who observed that this new device amplified by what might be termed "transfer-resistance" (Vacuum tubes amplified by transconductance.) The name was also in keeping with other semiconductor devices such as the thermistor and varistor.

The public birth of the transistor wasn't until the summer of 1948. A letter to the editor of the Physical Review on June 25th described "a three-element electronic device which utilizes a newly discovered principle involving a semiconductor as the basic element..." By then the design had been refined and a solid state superheterodyne receiver had been built at Bell. It used eleven point-contact transistors for the local oscillator, RF,IF and AF amplifiers. Germanium diodes were used for the mixer and detector, and selenium rectifiers for the power supply.

The First Production Transistor

The first manufactured point-contact transistors utilized an n-type germanium base. Dual two-mil tungsten wires made contact with the base at points about .002 inches apart. The structure was housed in a metal cylinder (tied to the base) with two protruding pins for the emitter and collector connections. It was designed to be plugged into a socket as vacuum tubes were.

Its operating parameters were very modest by today's standards. The maximum useful output power was about 25 milliwatts, the upper frequency limit was about 10 MHz and the noise figure was appreciably higher than that of a vacuum triode. These inherent limitations were offset by advantages such as low power consumption, zero warm-up time and small size.

The exact operating mechanisms of the point-contact transistor were never fully understood and though many theories were proposed, none seemed to answer all questions. Furthermore its characteristics were somewhat unpredictable and it was fragile. Fortunately by 1949 Shockley had developed his theory of p-n junctions and the junction transistor followed in 1951. Within a few years the point-contact transistor was rendered obsolete by the junction transistor, which continues to be widely used today.

The trio of inventors, Shockley, Brattain and Bardeen, were awarded the 1956 Nobel Prize in Physics in recognition of their achievement. Shockley established the Shockley Semiconductor Laboratory and played an important role in the development of additional semiconductor devices. Brattain was granted a number of patents and wrote many articles on solid state physics. Bardeen won a second Nobel Prize in Physics for his part in developing a theory on superconductivity. All three men survived to see the miniaturization and large-scale integration of the transistor.

Some Suggested Reading

1. "Ferdinand Braun and the Cathode Ray Tube," *Scientific American*, March, 1974, Page 92.
2. "The Transistor—A Crystal Triode," *Electronics*, September, 1948.
2. "The Transistor," by Frank Rockett, *Scientific American*, September 1948.
3. "How the Transistor Emerged," by Charles Weiner, *IEEE Spectrum*, January, 1973, page 24.
4. *Revolution in Miniature* (book) by Ernest Braun and Stuart Macdonald.
5. "Transistors in 1923?," by Ronald L. Ives, *CQ*, January, 1959, page 35.

***AMATEUR RADIO**, continued from page 23*

160 Meter QSO Party Results

BY MIKE RAIDE

This year's QSO party was bigger than ever (even though only in its second year!!!). There were 43 known participants, with W2ZM working 42 of them. Thanks to Hank, W6DJX, for getting on and working guys even in rough band conditions. I got on with the 1BCG transmitter and made several contacts, even working guys who had never worked that set before.

Thanks to all who participated, and thanks to all for your support. I will hopefully see everyone at the Conference!

73
Mike, W2ZE

KA1CFQ	9	W2KFG	19	W2YIK	10	W5WS	26
W1DDW	18	K2LGJ	15	N2YR	4	W6DJX	5
W1KSK	2	K2LP	20	W2ZE	27	KJ8L	17
WB2AWQ	17	W2LYH	22	W2ZM	42	W9POC	8
W2HBE	5	KB2PLW	8	K3DZ	24	K9VKY	11
KE2O	5	W4VBX	20	W3OER	11	J37XC	11
N2TWW	13	K5RB	7				

The following are known to have operated, but have not submitted logs:
W1ZR, W2AO, W2FB, K2IC, K2JVM, N2VO, W3DB, W3VVS, K4MOG, KD6B, W7FG, W7HB, NI8G, WA8JPC