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"The Invention of The Transistor--an example of Team Research"

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Introduction:

It's almost a cliché to say that the transistor has affected every person on this earth in one way or another. From wristwatches to cellular radios, from satellites to personal computers, cable TV to MRI machines and jet aircraft; and from Zaire to Alaska, and everywhere in between it would be difficult to find someone who hasn't been touched by that technology.

The transistor was invented nearly 50 years ago in December 1947 at the Bell Telephone Laboratories in Murray Hill, New Jersey. The inventors John Bardeen, Walter H.Brattain, and William Shockley shared the Nobel Prize in Physics in 1956 for their discovery. In the ensuing years the semiconductor industry was born, grew up and matured. Electronic companies around the world glommed onto that invention, and brought out redesigned radios and other marvels using transistors instead of vacuum tubes. Almost immediately brand new technologies sprung up that would have been impossible without the transistor and its grandchildren (integrated circuits; very large scale integration).

To the person on the street the electronics industry is taken for granted, a main segment of the world's economies. The electronics industry would have evolved in a markedly different direction had it not been for the invention of the transistor. Some of today's products literally would not be possible, typical examples for instance are the cellular phone handset; electronic wristwatches; the hearing aid; PCs; Satellite communications; and space probes. Imagine what these would be like if they were built with vacuum tubes. So in anticipation of the 50th anniversary of its invention, I want to create for you a picture of some of the events leading up to it, and introduce you to the three people involved.

Background - - *Radio Waves Across the Atlantic Ocean*

Let's go back in time to the beginnings of the communications age. It's December 12,1901 and Guglielmo Marconi, and his assistant Mr. Kemp are sitting in a hut on the cliffs of St. John's, Newfoundland. Marconi has just received a radio signal --the Morse code letter "s" (three dots) repeated several times, from his transmitter at Poldhu, Cornwall, England. The signal traveled 1700 miles across the Atlantic Ocean, from a spark gap transmitter to his receiver consisting of a few coils, a condenser, and a coherer. This achievement proved Marconi's theory that signals would propagate around the curvature of the earth. It ushered in the communications age.

The coherer was the most common detector in use back in those days; it consisted of a glass tube filled with metal filings, and when placed in a circuit with headphones, the filings cohered under the influence of a radio wave, suddenly lowering the circuit's resistance and thereby allowing a burst of current to flow, causing the operator to hear a buzz (a dot or a dash).

The chief defect of the coherer was its inability to maintain its sensitivity; the filings tended to stay packed together (same way as the early carbon granule microphones used in telephones); you had to shake them, or rap the tube against your hand to loosen up the filings.

Lee DeForest Invents the Vacuum Triode

Around this time Lee DeForest was in the process of trying to improve the sensitivity and efficiency of the coherer. He tried a liquid electrolyte as a substitute for the metal filings; in a later version of his device called a "sponder" gas bubbles on the electrodes maintained a high resistance in the receiver circuit and they quickly dissipated on the arrival of radio waves, dropping the resistance so that you would hear the signal in the earphones. The bubbles immediately reappeared in the absence of the radio signals, thus making the device self restoring. He went into the manufacture of sponders.

Earnings from the sponder allowed him to form the American DeForest Wireless Telegraph Company to compete with Marconi. DeForest, the scientist, was also a bit of a promoter-- his sponder didn't work any better than his competitors', but he used newspaper publicity to great advantage: articles about his wining a Gold Medal at the Louisiana Exposition at St.Louis in 1904, and on the use of the DeForest sponder in obtaining reports in the early days of the Russo-Japanese War in 1904-- these helped him gain U.S.Navy contracts. Keep in mind that the signals were in Morse code; dots and dashes--not voice.

But as he and his company began to use a new more sensitive version of his sponder, that bore a remarkable similarity to the detector patented by Reginald A. Fessenden, whose laboratories he had visited in 1904, he found himself embroiled in a patent infringement suit. He was discharged by the company directors in 1905.

DeForest then concentrated his efforts on wireless telephony-- voice, rather than wireless telegraphy-- Morse code. From an inspiration he had in 1900 while investigating the sensitivity of a gas flame to radio waves he began working with a gas filled diode. Incidentally, John Ambrose Fleming a consultant to Marconi, had developed the diode for use as a spark detector.

It was known at the time that if you heat a metal hot enough it will "boil off" some of its electrons; the electrons each negatively charged can be attracted to a positively charged plate. Now since the source of electrons is that red-hot metal the electrons-- the electric current-- will flow from it to the cold plate, but not from the plate to the hot metal. So the current flow will be uni-directional.

This first tube was a diode; it was used as a rectifier, for changing alternating current into pulsating direct current. The heater was a filament, a strand of wire, that got red-hot by passing a current through it, like the heater ribbon in a toaster. You placed these parts in a glass bottle, the neck was sealed around the wires and the bottle was connected to a vacuum pump. When the vacuum was good enough the evacuation neck was sealed off and the device was the vacuum diode. Alternatively one could put a gas such as nitrogen, never oxygen, in the tube, and have a gas diode.

In the years 1905 to 1907 DeForest and his assistant H.W.Babcock tried different arrangements of a third electrode in the vacuum tubes they were building; DeForest's work was clearly not as a result of theoretical insight, because it was only after trying out various arrangements of the heater filament or cathode, the plate or anode, and the third metal element that he hit on the correct arrangement. He tried mounting the third metal element in the form of a mesh, called a grid, between the cathode, and the plate. DeForest sealed this arrangement in a glass bottle as mentioned before; he was then able to change the flow of electrons that streamed from the cathode filament to the plate by changing the voltage on the grid. Increasing the grid voltage increased the plate current, and vice versa.

With this discovery he had invented the three element vacuum tube, a thermionic triode, which he called the *Audion* (H.W.Babcock suggested the name Audion); it could operate as a rectifier, or as an amplifier where the weak grid signal could be faithfully reproduced by the much stronger plate signal.

DeForest patented various types of Audion tubes, the most significant one in 1907. Paradoxically DeForest didn't immediately understand nor appreciate the significance of his invention despite his training in theoretical science; it was not until 1910 that he realized the triode's most significant features, its oscillating and amplifying capabilities. With the oscillating qualities he could make an oscillator that could generate radio waves! DeForest demonstrated his new technology on January 20, 1910 when he broadcast live opera featuring Enrico Caruso. The Radio Age had begun.

Manufacturing followed with improvements in triode characteristics, and longevity. Once the significance of the vacuum triode invention had dawned on the American Telephone and Telegraph Company (A.K.A. A.T.&T.) it managed by indirect means to buy the long distance telephony rights from DeForest in 1913, for a fraction of their worth. In 1914 A.T.&T acquired the radio signaling rights to the Audion; and from that time forward industrial research laboratories took over further development of vacuum tube technology. The hey day of the single scientist working in his laboratory was disappearing from the scene.

A.T.&T. saw applications for triode amplifiers as repeaters in their long haul telephone systems, and so set to work to understand the metallurgy, glass-to-metal bonding, emitter materials, and the best designs for vacuum tube triodes. They set up complete manufacturing lines at various Western Electric plants; the main strength of the A.T.&T. near monopoly was the reliability of the resulting vacuum tubes. A.T.&T.'s vacuum tubes were then the longest lived, and most consistent, albeit expensive. In later years A.T.&T. introduced a 50,000 watt version, which thereby made transcontinental radio broadcasting possible.

One of the tube types that they developed, called the AO1 triode, they continued to manufacture for the next 40 years, gathering data on its reliability all the while. It proved itself a worthy electronic component, for the type AO1 was used-- believe it or not -- in the first A.T.&T - British Post Office transatlantic telephone cable system, called TAT-1, from Clarenden, Newfoundland to Oban, Scotland put in service in 1956; it was the longest cable route at the time (1,945 miles, and carrying 74 voice circuits).

Crystal Radio Receivers and Boy Scientists

Early Radio relied on large high powered vacuum tubes, big antenna towers to broadcast music, news and comedy shows. To tune in to the stations, radio receivers that contained vacuum triodes, pentodes and tetrodes were being used. When you turned on the radio (receiver) you had to wait for it to "warm up"; what was happening was the individual vacuum tube filaments had to get hot enough to emit their electrons! The radios were costly, but if you liked to tinker you could make a *crystal radio receiver*.

A crystal radio receiver could be built by just about any tinkerer. In a book published in 1911 by Mr. A. Neely Hall it describes how the reader (Hall readership consisted mainly of boys) could build a crystal radio receiver. You had to wrap ninety turns of No.24 ga. wire carefully around a 4-inch diameter 'Mother's Oats' oatmeal carton; put up an aerial-- 50 feet of wire strung between two insulators, sometimes in an attic, often at parents' distraction, procure some ear-phones, a condenser, and a *galena crystal*. You didn't need a battery.

The galena crystal (galena is lead-sulfide) was the detector or rectifier in the radio receiver. To use it was tricky because you had to fiddle with little pointed wire called a "cat's whisker", and touch the tip of the wire to the galena at various spots, while listening on the earphones, until you found the right spot on the galena where the radio signal would be heard, then you left it alone. Success with tuning in a radio signal was often ephemeral with these makeshift receivers, and made especially difficult because of the thick thumbs of the tinkerer.

The term crystal is used often assuming an appreciation of its meaning, and importance. Most people are familiar with quartz crystals, rock salt crystals, and diamonds. We depart from the vacuum tube part of the discussion and pick up on crystals, because work on certain kinds of crystals paved the way to the invention of the transistor.

A crystal is nature's ultimate example of orderliness. The atoms in a crystal are arranged in a three dimensional lattice-- for illustration think of the lattice that rosebushes cling to;it is a two-dimensional lattice; each intersection of the rose lattice model could represent an atom; the atoms would be arranged in rows and columns. Now imagine a repetition of rose lattices side by side; an array of two-dimensional lattices, and you have a concept of a three-dimensional lattice. This is similar to the way the atoms are arranged in a crystal. Each atom in a crystal is a certain distance away from the other atoms.

A crystal is truly an orderly substance-- 'out of chaos, order' could be nature's guideline for a crystal's formation. As a counter example-- a pot of clam chowder bubbling on the stove is an example of a disorderly substance-- it is chaos in action.

Most important to the discussion leading to the transistor was that the use of galena crystals in these do-it-yourself receivers represented the first crude point contact semi-conductor diodes to be used in electronic circuits. The time period was roughly from 1912 to well into the 1930's. Some of the kids who liked to tinker with these receivers were budding scientists, and three of them would go on to invent the transistor.

John Bardeen

John Bardeen was born May 23, 1908 in Madison, Wisconsin. As a boy he had great interest, and curiosity about radios, cars and airplanes. He was 10 years old when the "great war" was over. That he built and experimented with crystal radio receivers I have no doubt. He would have been intrigued by that curious little galena crystal that provides the detection capability in the receiver. This would be very prophetic since crystals, made of a germanium would later form the basis of his later work.

John Bardeen was an excellent student, being influenced at home by his father, Charles Russell Bardeen, who was professor of anatomy, and dean of the University of Wisconsin, and grandfather Charles William Bardeen, author and educator. John Bardeen was the eldest of three boys, excelled in school so that he earned his B.S.degree in electrical engineering at the age of 20, the year was 1928. The following year he earned an M.S in E.E. Both degrees were from the University of Wisconsin.

He worked at Gulf Research and Development Corporation in Pittsburgh for three years starting in 1930, as a geophysicist. Bardeen left Pittsburgh in 1933 to study at Princeton University Graduate School in New Jersey. He received his Ph.D. in Mathematics and Physics from Princeton in 1936. He had also studied at Harvard University at the same time, as a junior fellow of the Society of Fellows. In 1938 he was appointed assistant professor of Physics at the University of Minnesota. Through his work there, he was becoming an authority on solid state theory concerning metals, matter and semiconductors.

Bardeen left the University of Minnesota in 1941 to become the principal physicist at the Naval Ordinance Laboratory in Washington, D.C. At the end of World War II in 1945, he became a research physicist at the Bell Telephone Laboratories at Murray Hill, New Jersey.

Walter H. Brattain

Walter Houser Brattain was born on February 10, 1902 in Amoy, China to Ross R. Brattain and Ottilie Houser. His father was a private school teacher; and shortly after Walter was born the family moved back to the state of Washington. Walter grew up in Washington, and graduated from Whitman College in Walla Walla with a B.S. Degree in 1924; he was elected to Phi Beta Kappa, and Sigma Xi science research honorary fraternity. He received his M.A. Degree in 1926 from the University of Oregon at Eugene, then earned the Ph.D. degree at the University of Minnesota in Minneapolis in 1929.

Dr. Brattain worked for one year at the Bureau of Standards, Washington,D.C., and was a co-designer of a portable temperature controlled oscillator. In 1929 he joined the technical staff of the Bell Telephone Laboratories, and worked initially in the field of thermionic emission from hot surfaces, substantially increasing the knowledge of how impurities on the surface affect electronic emission. He was a hands-on laboratory experimenter designing and constructing experimental equipment, making measurements, analyzing results, and reporting on them in internal Bell Telephone Laboratory reports.

William Shockley

William Shockley was born on February 13, 1910 in London, England, and his parents William Hillman, and May (Bradford) Shockley brought him to the United States when he was three. He was reared in California, and attended Hollywood High School, graduating in 1927. He graduated with a B.S. E.E. from Cal Tech in 1932. Shockley was then appointed to a teaching fellowship at M.I.T., where he concurrently worked on the Ph.D. in physics. When he received his doctorate in physics, he joined the Bell Telephone Laboratories as a member of the technical staff in 1936.

Dr. Shockley was interested in finding a substitute for the bulky, and costly three-element vacuum tube-- the triode-- that DeForest had invented 30 years earlier. He had long held beliefs that the limitations of the vacuum tube could be surpassed by using semiconductor devices.

Shockley started experiments at the Labs in 1939, aimed towards making a semiconductor amplify as well as rectify. His colleague Dr.Brattain also took up the study of electrical conductivity and rectification phenomena in semiconductors, with a major portion of his attention devoted to copper-oxide varistors. He also studied the properties of silicon and germanium.

These early experiments were unfruitful, though good background information was gained. Their work was interrupted when both Shockley and Brattain were assigned by the U.S.Navy during World War II to work on anti-submarine warfare at Columbia University, in New York City. Shockley went as director of research, for the ASW operations research group. Dr. Brattain was a key researcher on magnetic detection of submarines.

Drs. Brattain and Shockley returned at the end of W.W.II to the Bell Labs in 1945, just about the time that Dr. Bardeen became a member of the technical staff there. From his previous studies Shockley had concluded (on paper at least) that it was possible to control the supply of moveable electrons inside a (crystal) semiconductor by influencing them from an electric field imposed from the outside. The atoms in the crystal lattice would shield somewhat the electrons deep within the crystal, of course, but *it is to this conclusion that the genesis of the transistor is traced.*

In actual experimentation the electrons kept getting tangled up in the surface of the material, and the results were negligible. But Shockley was convinced that it could be done and urged that a program of research work be started to make a solid state device that would be a replacement of the DeForest vacuum tube. The problem was that Shockley and Brattain did not have a true theoretical model of what was going on in the bulk of the crystal semiconductor nor, more importantly at the surface and interfaces between the bulk crystal and the metal contacts.

Formation of the Team

A team was formed following the successful strategy used throughout the Bell Laboratories to attack problems of great technological impact on their communications business: that is to bring together theoreticians, laboratory experimentalists under the tutelage of what could best be described as a "mentor" (or cheerleader?) to guide the work. Shockley was the senior man, the mentor, Brattain the experimentalist, and Bardeen the theoretician in this team. Supporting staff members were on board too, such as technicians, and entry level assistants.

Selecting germanium and silicon as the best candidate semiconductor materials to work with, the Bell Labs set up an intensive program under the direction of Shockley, and S.O.Morgan to understand the properties of these materials. They worked with crystals because they are the simplest fundamental structure, the atoms of the crystals are at predictable locations one from another, and already some properties were known about these structures. To deal with amorphous semiconductors would introduce too many degrees of uncertainty to sort through; it would have complicated the problem enormously. They had to have chips of pure crystalline germanium, and silicon.

Dr. Brattain, a brilliant research physicist, led the actual physical experimentation--he built the experimental devices and made the measurements on them. Two members of the team, Brattain and Shockley, already had formed a strong working relationship from previous projects at the Labs.

Two groups commenced working on understanding the properties of germanium and silicon; one group on the bulk properties of (crystal) semiconductors and the other on the surface properties. A chemist , R.B.Gibney worked for both groups; he grew the crystals needed, and saw to it that the correct impurities were introduced in them.

Bardeen's Theory was the Key to Success

They were trying to understand --to create in their minds a model, or models of how electrons propagate through the crystal, and what happens at the interfaces between crystals of different makeup--different dopings--and between the crystal surface and the metal contact. The interface properties were crucial, because little was known about the physical processes that were taking place at the interfaces. They were at first not able to predict with a given set-up what would happen.

John Bardeen proposed a theory involving surface traps to explain why the device didn't work. This led to more physics experiments to learn more about surface traps and their energy states. It was like having snipers (traps) at the edge of a forest, next to an open field (metal contact)--when the electrons came along to get out of the forest (semiconductor) and cross the field they were picked off--shot dead. Not many could escape. It meant that the crystal surfaces, and interfaces had to be made with great care.

In the work, devices would be mounted in a holder, temperature would be held constant, the device would be connected to a power supply; currents and voltages would be measured. Just as the "cat's whisker" was manipulated to find the right spot on the galena crystal, they positioned their point contact probe , but in this work using a micrometer, to get repeatable results. Readings of all the variables were taken methodically and the findings were noted. Brattain would set up the experiment, make the measurements, Bardeen would make a suggestion, and Shockley concur, and keep them on course.

The key experiment involved a germanium diode immersed in an electrolyte (a solution that conducts electricity) and connected to a source of direct current. This, Bardeen and Brattain reported, led to the concept that the current was being carried through holes-- electron vacancies in the atoms-- flowing near the surface. Upon replacing the electrolyte with a metal contact, transistor action was discovered.

When the test results showed consistently that under the proper bias-voltage conditions this three element device produced gain--that is that it amplified a high frequency but feeble input signal--they realized that they had achieved their goal. The result was the invention, announced in 1948 (actual discovery was December 23, 1947), of the "transistor" the name being an abbreviation of "transfer" and "resistor". The device was described as 'a compact and rugged point contact device which without vacuum, grid, plate, or (hot) cathode--and requiring only one-fiftieth the space of a vacuum tube and one-millionth the power can perform most of its functions and even extend them'.

(Take that Lee DeForest!!)

Scientific and technical journals and other works of reference credit the invention of the transistor to Bardeen and Brattain jointly, while Dr.Shockley "fathered it ...by advancing the hypothesis and pointing the way."

Epilogue

Bardeen, Brattain, and Shockley remained colleagues at the Bell Laboratories until 1951, when Bardeen was appointed professor of electrical engineering and physics at the University of Illinois. Dr. Shockley left the Labs to become director of Shockley Semiconductor Laboratory of Beckman Instruments, Inc. Dr. Brattain retired from the Labs at age 65.

Honors to the Inventors:

Nobel Prize in Physics jointly to Shockley, Bardeen, and Brattain on November 1, 1956, "for their investigations on semiconductors and the discovery of the transistor effect." They shared $38,634.

To Dr. Brattain:

- Honorary Doctor of Science from University of Portland (Oregon) in 1952
- Franklin Institute Medal (Philadelphia), shared with Bardeen in 1952
- Stuart Ballantine Medal in 1952, shared with Bardeen
- John Scott Medal in 1955, shared with Bardeen
- Physics Prize of $1000 shared with Bardeen in 1955
- Honorary D.Sc. degree from Union College and University of Schenectady, NY in 1955
- Honorary D.Sc. degree from Whitman College, his *alma mater* in 1955.

To Dr. Bardeen:

- Franklin Institute Medal (Philadelphia), shared with Brattain in 1952
- Stuart Ballantine Medal, shared with Brattain in 1952
- John Scott Medal, shared with Brattain in 1955
- Physics Prize of $1000 shared with Brattain in 1955
- Honorary D.Sc. degree from Union College and University of Schenectady, NY in 1955
- Oliver E. Buckley Solid State Physics Prize of the American Physical Society in 1954

To Dr. Shockley:

- Medal of Merit, in 1946 from U.S. War Department
- Certificate of Appreciation from Department of the Army in 1953
- Morris Liebmann award of Institute of Radio Engineers in 1952
- Oliver E. Buckley Solid State Physics Prize of the American Physical Society in 1953

In 1970 I met William Shockley at a Sigma Xi Banquet, in New Jersey. He was the speaker, and his current "theories" were that the black race suffered from gene-related intellectual inferiority!

Bardeen shared a second Nobel Prize in Physics in 1972, with Leon Cooper and Robert Schrieffer for a new theory of Superconductivity.

Brattain said when informed of the honor--the Nobel Prize:"It is a great satisfaction to have done something in life and to have been recognized for it in this way. However, much of my good fortune comes from being in the right place, at the right time,and having the right sort of people to work with."