A HISTORY OF SEMICONDUCTORS

FROM THE ARCHAIC

TO THE MONOLITHIC

Compiled by

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Introduction

I have recently been through a convergence of events that has led me to enthusiastically write this historical survey. Books offered to me from several friends regarding electronics and with "Crystal" in their titles appeared to me unsolicited. These have revived one of my earliest memories that is of a crystal radio from the mid-1950s. I'm now at an age where history is far more appealing to me than it was in high school. And only now with these books have I wondered about the earlier history of semiconductors leading to the monolithic circuit. There never was any history of semiconductors taught to me in college and I suspect that is the norm. With that in mind I decided to write a brief history on the subject so that I would belatedly come to know it and pass it on to others in the industry, who like me, had never learned it. It seems that with the substantial effort put into acquiring knowledge of electronics and into many hours at work, one should come to know the history sooner than later. Knowing what limited time many have I have strived to limit this article to just a few hours of interesting reading and have included only the most pertinent and intriguing people and facts that I could mine out of the data (some important discoveries were made by accident!). Regrettably, many other contributors have been omitted. It is my intent that this article get widely circulated for the benefit of semiconductor workers and others with interest, so please freely send a copy to whomever you desire and encourage them to do so as well.

It is important to note that without a steady supply of electrons from a voltage source and at least some primitive measurement apparatus that semiconductor discoveries could not be made. Thus these discoveries had to wait at least until the voltaic pile was invented in 1800 by Volta and perhaps until the longer lasting Daniell cell was invented in 1836 (used for 100 years). The first moving pointer current detecting device was the galvanometer invented in 1820. These were used to measure resistance and voltage by using a Wheatstone bridge and comparing the unknown quantity to a reference voltage or resistance. Germanium was predicted in 1869 from the periodic chart and found in 1886. Silicon was first characterized in elemental form in 1824.

The history of semiconductors reaches back as far as 1833 and through the remaining 1800's "experimentalists" discovered some of its basic properties, but without any fundamental understanding. Basic applications began to appear for AM detection of wireless signals by crystal detectors in the 1890's. Theoretical understanding of semiconductors was achieved in the 1930s-1950s followed by rapid advances leading to the monolithic integrated circuit. Over the course of this history presentation I will cover the essential details required to form an appreciation for the efforts of experimentalists, engineers, physicists, chemists, material scientists, technicians and support personal who made modern microelectronics possible.

1833-1907: The Experimentalists

During the time period of 1833-1907 the experimentalists discovered basic properties of semiconductors that include: negative temperature coefficient of resistance, photoconductivity, rectification, photovoltaic effect and electroluminescence.

We start with **Michael Faraday**, FRS (22 September 1791 – 25 August 1867), an astonishing experimentalist with many achievements and seminal works in science.

Faraday studied the magnetic field around a conductor carrying a DC electric current. While conducting these studies, Faraday established the basis for the electromagnetic field concept in physics, subsequently enlarged upon by James Maxwell. He similarly discovered electromagnetic induction, diamagnetism, and laws of electrolysis. He established that magnetism could affect rays of light and that there was an underlying relationship between the two phenomena. His inventions of electromagnetic rotary devices formed the foundation of electric motor technology, and it was largely due to his efforts that electricity became viable for use in technology. As a chemist Faraday discovered benzene, investigated the clathrate hydrate of chlorine, invented an early form of the Bunsen burner and the system of oxidation numbers, and popularized terminology such as anode, cathode, electrode, and ion.

Although Faraday received little formal education and knew little of higher mathematics, such as calculus, he was one of the most influential scientists in history. Historians of science refer to him as the best experimentalist in the history of science. The farad is named after him as is the Faraday constant, the charge on a mole of electrons (about 96,485 coulombs). Faraday's law of induction states that magnetic flux changing in time creates a proportional electromotive force. Faraday was the first and foremost Fullerian Professor of Chemistry at the Royal Institution of Great Britain, a life-time position.

In 1833 Faraday’s experimental work in chemistry led him to the first documented observation of a material that we now call a semiconductor. While investigating the effect of temperature on "sulphurette of silver" (silver sulfide) he found that electrical conductivity increased with increasing temperature. In a chapter titled "On Conducting Power Generally" in his book “Experimental Researches in Electricity”, Faraday writes "I have lately met with an extraordinary case … which is in direct contrast with the influence of heat upon metallic bodies … On applying a lamp … the conducting power rose rapidly with the heat … On removing the lamp and allowing the heat to fall, the effects were reversed." This effect, due to a dramatic increase of carriers with increased temperature, was the opposite of what he measured in metals.

Alexandre-Edmond Becquerel (24 March 1820 – 11 May 1891) was a French physicist who studied the solar spectrum, magnetism, electricity, and optics. He is best known for his work in luminescence and phosphorescence. In 1839 he recorded his observation of photovoltage in silver chloride (AgCl) coated electrodes. In his experiment a coated platinum electrode was immersed in a nitric acid electrolyte solution to make a voltaic wet cell. Illumination of the electrode generated a photovoltage that altered the voltage produced by the cell. Photovoltage was generated at the Ag/AgCl metal semiconductor contact. The silver at the junction was formed by silver clusters absorbed in the electrolyte solution from the electrode coating.

Willoughby Smith (6 April 1828 –17 July 1891) was an English electrical engineer who discovered photoconductivity with the element selenium. In 1849 Smith superintended the manufacture and laying of 30 miles of underwater telegraph wire from Dover to Calais. He worked closely with English scientist Charles Wheatstone who had designed the machinery for making and laying the cable. In 1873 Smith developed a method for continually testing an underwater cable as it was being laid. For his test circuit he needed a semiconducting material with a high resistance and selected selenium rods for this purpose. The selenium seemed to do the job properly, except in actual use the device gave inconsistent results. Upon investigation, it was discovered that the conductivity of the selenium rods increased significantly when exposed to strong light. Smith described the "Effect of Light on Selenium during the passage of an Electric Current" in an article that was published in the 20 February 1873 issue of Nature. This discovery led to the invention of photoelectric cells, including those used in the earliest television systems.

Charles Fritts (27 February 1850 – ?) was an American inventor credited with creating the first working solar cell in 1883 by using the photovoltaic effect of semiconductors to create electricity. Fritts coated the semiconductor material selenium with an extremely thin layer of gold. The resulting cells had a conversion efficiency of only about 1% owing to the properties of selenium, which in combination with the material's high cost prevented the use of such cells for energy supply. Selenium cells found other applications as light sensors for exposure timing in photo cameras.

In 1874 German physicist **Ferdinand Braun** (6 June 1850 – 20 April 1918) discovered rectification. His interest in the electrical conductivity of metal salts in solution (electrolytes) ultimately led to his study of crystals. He was studying the passage of currents through a crystal of galena (lead sulfide) when he discovered that they flowed only in one direction (rectification) if one of the two metal contacts was pointed. He found more than 250 minerals that were capable of rectification when used in conjunction with a metal contact or with another mineral (then called "Perikon"). Some of the more successful minerals include galena, pyrites, bornite, zincite, and silicon. In 1897 he built the first cathode ray tube and cathode ray tube oscilloscope. Braun's other contributions included a new type of transmitter not requiring the spark-gap that Hertz and Marconi had been using. His 1904 patent on the resonant circuit allows tuning to the frequency of interest. In early wireless transmission broadcasting was limited to a range of about 15 kilometers. Braun greatly increased the range by producing a sparkless antenna circuit that linked transmitter power to the antenna circuit inductively. Marconi would later admit to Braun himself that he had "borrowed" portions of Braun's work. In 1909 Braun shared the Nobel Prize with Marconi for their contributions to wireless telegraphy.

In 1899 Braun found that using his crystal rectifier as a radio signal detector provided no improvement over the coherer when the wireless telegraphy messages were automatically recorded on a moving strip of paper, as was the normal practice with spark-gap transmitters at the time. By 1901 the advantage in transmission range of having a human telegraph operator with headphones use sensitive hearing to decipher the messages was recognized. Now Braun's crystal detector was found to be superior to the coherer. When transmitters that produced pure continuous wave (CW) oscillations for Morse code became available, neither the coherer nor Braun's crystal detector produced a response. However, others soon improved his crystal detector for use as an inexpensive and reliable detector for radiotelephony.

India born **Sir Jagadish Bose** (30 November 1858 – 23 November 1937) obtained the first patent for a galena detector, 755840, issued in 1904.

General Dunwoody (23 October 1842 – 1 January 1933) of the U.S. Army was among the first to put the crystal detector to practical use with his patent 837616 on the carborundum (silicon carbide) detector. The crystal rectifier was far superior in detecting the audio in the emerging AM radio broadcast signals than were the poor sensitivity coherers and later became useful for CW code as well. It was the first sensitive and stable detector. Coherers consisted of glass filled tubes with fine metal filings in the space between two electrodes. The metal filings are attracted under the influence of a sufficiently high electric field from a radio transmitter. Once attracted, a strong electrical conduction path is established to operate a relay or buzzer through which Morse code could be heard as the transmitter was keyed on and off.

The American **Greenleaf Pickard** (14 February 1877 – 8 January 1956) improved upon crystal rectification by making it more practical and utilizing it as a detector for CW radiotelegraphy transmissions. He was granted patent 836531 in 1906 for the improved silicon crystal detector. He found that a finely pointed wire known as a "cat's whisker", in delicate contact with a mineral, produced the best detector effect. His claim stated “As an element of a means for receiving intelligence communicated by electric waves, the substance silicon**,** substantially as and for the purpose described”. His patent’s illustration clearly depicts a “spring which presses the sleeve-contact” metal point against silicon to produce a radio detector. The principle of detection was incorrectly stated in the patent as “generation of heat into electrical energy at a thermo-junction and of the generation of electrical energy by the heat energy at a thermo-junction”. Pickard was eventually granted many patents relating to radio. His silicon and carborundum crystal detectors were first produced and marketed in 1906.

English **Captain Henry Joseph Round** (2 June 1881–17 August 1966) was one of the early pioneers of radio and received 117 patents. He was the first to report observation of electroluminescence in the form of a yellowish glow emanating from a carborundum (silicon carbide) detector in 1907, thus discovering the light-emitting diode. He was a personal assistant to Guglielmo Marconi.

1906-1920s: Early Commercialization of the Semiconductor

A partnership between Pickard and **Philip Farnsworth** in 1906 produced the Wireless Specialty Apparatus Company (WSA) that began selling crystal detectors in 1907. When the Canadian inventor and pioneer of radio, **Reginald Fessenden,** sent the first voice radiotelephony transmission from near Boston in late 1906 the crystal rectifier was already well established for detection. At the time few, including Edison, believed that the transmission of voice was possible. Fessenden lost control of many of his patents and the royalties from his radiotelephony made others rich. He went on to invent the radio compass and even to demonstrate a crude television system in 1919.

The most common early crystal detector consisted of the crystal, crystal holder, mounted yet adjustable metal probe for contacting the crystal’s surface and terminals for connection to a receiver’s circuit. The probe was usually a spring loaded cat’s whisker made of springy phosphor bronze wire. Experimentation with probe position and pressure was required to obtain good performance that could be easily upset with an unintended vibration. Fixed sealed detectors that were less sensitive to vibration came about in the mid-1920s. These were often in cartridge form. Some adjustable units could hold up to six different types of detector materials that the user could select as needed. Other detectors were enclosed in a glass cylinder capped on the ends with various materials to keep out dust and dirt. These were adjustable by use of a movable rod with a cat’s whisker that poked through a port in one end. Some adjustable units had several controls for adjustment. Detector performance often depended on the particular mine from which the mineral came. At this time, how crystal detectors worked was a mystery.

Until 1919 crystals were usually sold unmounted for use in a detector that often had a holder available for the crystal. Distributors put little effort into packaging these. By 1920 individual crystals were usually mounted with Wood’s metal or thumbscrews inside of a cup style metal holder and were displayed for sale in attractive colorful boxes. The boxes were usually made of tin, wood or cardboard and were in rectangular or round pillbox form. A few were offered in a plush jewel type hinged case.

Between the mid 1910s and mid 1920s an ever growing number of companies produced unmounted crystals and crystal detector units that included a crystal mounted in a holder on a base, cat's whisker with adjuster and terminals. These came in a great many usually attractive forms. Bases made of Bakelite, hard rubber and wood were common, but elegant marble was available as well. In their trade names or mottoes companies made various claims regarding volume (T.N.T. High Power), clarity (Krytal-Kleer), tone (Clara Bell) and sensitivity (Hot Spot) to differentiate between products. Ad claims such as these were common: "Clearer tone, greater volume, longer life than other detectors.", "Absolutely the best crystals that can be purchased at any price." and "Radio engineers pronounce it the only electrically and scientifically perfect crystal detector." A few manufacturers offered stabilized detectors that included a rheostat and a one or two cell battery for biasing the crystal. The biasing would lower the detection threshold resulting in higher volume and sensitivity. Others claimed that various gases could be fed into their sealed detectors through a port to enhance performance.

Crystal detectors first found widespread use in ship to shore and military communications. By 1919 WSA had entered agreements for crystal detector manufacturing with other companies such as General Electric (GE), Radio Corporation of America (RCA), American Telephone and Telegraph (AT&T) and Westinghouse. Philmore Mfg. (1921) produced crystal set items for 60 years and Western Manufacturing (1932) for 30 years. Crystal detector prices in past dollars typically ranged from $1.00 to $ 6.00.

Since the detector needed other components to function as a radio receiver, companies were quick to develop these as well. Crystal receiving sets were offered by WSA starting in 1907 with its basic IP-76 model. Sets were comprised of a case or a simple base, crystal detector unit and inductor-capacitor tuning circuit to which an antenna (often called "aerial" then), ground and headphones could be attached. Antennas were usually 50'-150' of strung wire. They frequently had a broad tuning range of 200 meters (1500KHz) to 3500 (86Khz) meters that covered the 2500 meter time signals sent by the Navy from Arlington, Va. starting in 1913. The time signals were often used as a test signal or by jewelers to set timepieces. By 1914 some sets were complex instruments with many controls, connectors and meters on their panels. A buzzer accessory was sometimes used to create a signal for calibrating the cat's whisker.

1930s-1950s: Theoretical Advances and the Transistor

The German word "halbleiter" was first used in 1911 to describe semiconductor materials with electrical conductivities between those of conductors and insulators. A good explanation of semiconductor behavior eluded scientists for decades. As late as 1931, physicist Wolfgang Paul noted "one shouldn't work on semiconductors, that is a filthy mess; who knows whether any semiconductors exist." While working at Werner Heisenberg's institute in Leipzig, Germany that same year, Cambridge University physicist **Alan Wilson** adapted the quantum theory of solids being developed there by **Felix Bloch** and **Rudolf Peierls** to create a model of semiconductor behavior. In two papers titled "The Theory of Electronic Semi-Conductors," he proposed that their peculiar properties were due to the presence of impurity atoms in otherwise pure crystals of these materials. In 1932 Wilson also tried to explain the one-way current flow in a point-contact rectifier as due to quantum-mechanical tunneling between metal and semiconductor. But along with attempts from other scientists in the early 1930s, his explanation eventually proved wrong. Satisfactory explanations of rectification finally emerged in 1938. **Boris Davydov** at the Ioffe Physico-Technical Institute of the Russian Academy of Sciences, Leningrad; **Nevill Mott** at Bristol University, England; and **Walter Schottky** at Siemens and Halske in Munich, Germany independently attributed the phenomenon to a concentration of electrons on the semiconductor surface that set up an asymmetric barrier to current flow.

The first working transistor had three primary fathers, all of whom stood on the shoulders of giants Heisenberg, Einstein, Pauli, Maxwell, Faraday, Dirac, Bohr and von Neumann. They were **William Shockley**, **John Bardeen** and **Walter Brattain** who all worked at Bell Labs in Murray Hills, NJ. All had tinkered with crystal radios in their youth and all had Ph.D. degrees in physics. In 1932 Shockley entered MIT to seek his Ph.D. where Linus Pauling suggested that he study quantum mechanics. He began to explore how electrons pass through crystalline materials such as salt and this was the first attempt to apply quantum mechanics to a compound rather than a pure element. The cerebral Bardeen skipped three grades in high school and started college at age 15 where he earned two degrees in electrical engineering. Dirac's lectures on quantum mechanics led him into physics. His dissertation involved calculating the energy required to free an electron from a sodium atom. He was often lost in thought and spoke softly thus earning the nick name "Whispering John". He was considered an oracle, so when he spoke he was listened to. During the 1920s Brattain found ways to enhance electron emission efficiency in tubes using thorium or tungsten and he developed a portable crystal oscillator standard while working for the National Bureau of Standards. Intrigued by the newly invented copper-oxide rectifier that could be used as an AM detector, Brattain studied it in hopes of understanding how it worked. Understanding it would lead to advances, but by the 1930s there was only a rudimentary understanding. At the time physicists were just beginning to explain rectification in semiconductors such as in crystal detectors. In the case of copper-oxide rectifiers something set up an asymmetry between the copper and copper-oxide layer. This was not well understood until the late 1930s. Brattain had said "Ah, if only one knew how to put the third electrode in the cold rectifier like a grid in a vacuum tube one could have an amplifier". He was influenced by provocative articles about the newest developments in quantum theory emerging from Europe and lectured at Bell Labs on the quantum theory of electrons in metal. European theoretical physicists of the time where intensely studying and developing quantum mechanics while the practical-minded Americans began to employ the new quantum tools to their research into atoms, molecules, metals and crystals. Brattain joined Bell Labs in 1929, Shockley in 1936, and Bardeen in 1945.

Bell's research director encouraged Shockley to seek ways to fabricate a rugged solid-state device to replace the bulky and unreliable mechanical switches and amplifiers found in phone equipment. He said that he looked forward to the time when metal contacts would be replaced by electronic devices. Shockley organized a weekly study group of scientists at work to discuss recent books on atomic physics and quantum mechanics. In 1939 Shockley's familiarity with quantum physics led him to an idea for a transistor. On the 29th of December he wrote "It has occurred to me that an amplifier using semiconductors rather than a vacuum is in principle possible". With Brattain's help his idea was fabricated, but it was a complete failure. Better insights into solid-state theory and purer semiconductor materials were needed for further progress. Just prior to WWII, Ph.D. scientists fleeing Hitler and

Mussolini had bolstered U.S. university physics departments, but the war effort interrupted the theoretical research into semiconductors. Shockley's, Bardeen's and Brattain's efforts were directed to war research. However, semiconductor technology took a leap forward during World War II as radar receivers needed solid-state rectifiers to detect and convert microwave signals at frequencies higher than possible using vacuum tube diodes. Silicon and germanium emerged as the dominant semiconductor materials due to wartime R&D efforts made in part by Bell Labs. By 1941 purity levels of 99.99% were achieved. With such purity, desired impurities could be added to consistently produce either P or N type material.

After the war and upon returning to Bell Labs in 1945, Shockley began organizing Bell's solid-state research program under director **Mervin Kelly** (future president of Bell Labs). Since 1936 Kelly had dreamed of finding electronic substitutes for mechanical relays in telephone exchanges. He set up the first solid-state research program in the 1930s. There was now a new emphasis on the physics and chemistry of solids. Quantum physics research was promising new materials with new and useful properties. Kelly wanted to fashion the equivalent of the mission oriented multidisciplinary research teams that proved so effective during the war. Shockley also headed a sub-group of Solid-state Physics. Brattain joined this team.

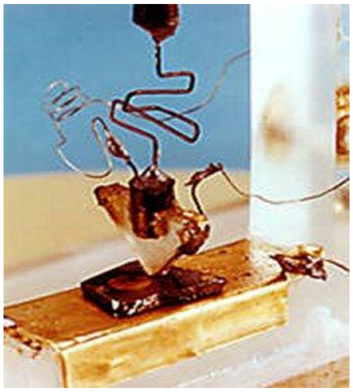
Researcher **Russell Ohl** briefed Shockley about his experimental work with P-N junctions, the photo-voltaic effect and methods of processing silicon for detectors that he had been studying at Bell since the mid 1930s. Ohl also tested over a hundred materials for use as detectors and found silicon to be by far the most sensitive. One still needed to hunt around it with a cat's whisker and even a movement of a thousandth of an inch might make it rectify in the opposite direction. Ohl suspected the variability was due to impurities and he decided to purify silicon. In 1939 he got help using an electric furnace filled with inert helium to melt silicon in quartz tubes placed inside. After cooling the quartz was cracked to recover black polycrystalline silicon ingots. These were much more uniform for rectification, but some ingots rectified in one direction while others in the opposite.

On February 23rd 1940, Ohl tested a silicon rod that was of particular interest. It had peculiar and unrepeatable electrical qualities across it and it was able to create voltage from light. A fan placed between it and a light source produced a frequency at which the fan blades shadowed the rod. He also noticed that different parts of the crystal yielded opposite electrical effects when tested with a cat's whisker style probe. The ingot from which this rod was made had been cooled very slowly to help avoid cracking, but this allowed impurities time to separate across the ingot into two regions. Ohl and colleague **Jack Scaff** found that the rod happened to be cut where there were impurities of one type on one side and of another type on the opposite side thus producing the unrepeatable electrical qualities across it. One impurity, the element phosphorus, yielded a slight excess of electrons while the other, boron, led to a slight deficiency. Where the two regions met the junction formed a barrier to electron flow in one direction. On one side there were excess electrons and on the opposite a deficit due to the kinds of impurities. A barrier arose when electrons rushed from one side to the other causing a stabilizing electric field to be established. This field would oppose current flow in one direction while not the other. It was light sensitive because photons dislodged some electrons from the silicon. Ohl and staff realized they had stumbled across an important phenomenon and named one junction side P and the other N. Current would flow if positive voltage were applied to the P side and negative on N side. The P-N rectifying junction was discovered by accident rather than invented!

Intrigued by Ohl's earlier experiments, Shockley said "Did you ever think that if you put a point-contact at the barrier that you could get control of the current flowing through?" Both men had ideas for controlling current through the silicon by use of very thin metal plating between the junction. Using quantum theory, Shockley proposed changing the behavior of narrow P and N type materials with a strong electric field applied at their junction. The easily controlled fields, he thought, should cause electrons or holes to move as directed thus changing the semiconductor's conductivity. He referred to this as a "solid-state valve". Experiments with a thousand volts across a narrow gap of <1mm above the silicon resulted in no change of current flow. Calculations said a large current change should commence. He soon abandoned these particular efforts for awhile. New ideas came about after Bardeen was hired. He had come up with the key ideas, which were skillfully implemented by the genial Brattain. Shockley asked him to check his calculations concerning the "field effect" with which he had hoped to make a solid-state amplifier. He confirmed Shockley's calculations. Later Bardeen realized that the electron wave function extends slightly beyond that of the ions at the crystal's edge thus leading to excess negative charge at the surface and excess positive charge just beneath it. If electrons were trapped at the surface as "surface states" in N type silicon they would form a shield thus preventing an applied external field from having effect. In 1946 he revealed his theory at a group meeting. This double charge layer explained many phenomena that eluded other theorists including Shockley. Amplifying device attempts were abandoned in favor of experiments with surface states led by Brattain. Attempts were made to search for a field-effect in a thin germanium film vapor deposited on ceramic. This time they saw the field-effect Shockley had expected with a mystifying 0.1% change in conductivity. Two factors for poor performance were surface states and low electron mobility. Shockley's other interest in surface states was clinging precariously to the stone walls at Bell Labs during lunch break!

By 1947 Brattain's experiments of light effects with an electrode on cooled silicon in a thermos produced enhanced photo effects. To keep condensation away he had filled the thermos with alcohol. He and chemist **Robert Gibney** discovered that a positive voltage increased the photo effect, while a negative could eliminate it. With this accidental discovery Brattain realized he could effectively control the charge on the silicon surface. This apparatus was very similar to earlier experiments to search for the field-effect except that it had a liquid between the plate and semiconductor. Liquid electrolytes that contain positive and negative ions worked best. Under the influence of an electric field these mobile ions migrated to the silicon surface where they enhanced or reduced the charge density there. This "electrifying" breakthrough in field-effects, which would allow a semiconductor amplifier to work, swept through the semiconductor group (the field-effect transistor is ubiquitous in today's electronics).

A few days later Bardeen suggested to Brattain a new way to make an amplifier by jabbing a sharp metal point onto a piece of silicon surrounded by an electrolyte. They used a slab of silicon and coated the tip of a sharp tungsten wire with liquid wax to insulate it from a drop of distilled water on the silicon. With the tip on the silicon and the water contacted with an electrode they were able to alter the current through the silicon 10% by varying the water voltage. Because the input control current was smaller than the output current the device was amplifying current and power! Brattain told others "I'd taken part in the most important experiment that I'd ever do in my life". He realized they had stumbled onto something big because they demonstrated that it is possible to effectively control and amplify current in a semiconductor. Shockley became excited by the developments and suggested a few ideas of his own. One was to apply an electrolyte that they extracted from electrolytic capacitors (glycol borate) directly across a P-N junction and use it to control the current. This succeeded and further hastened the feverish pace of discoveries and breakthroughs that elevated power gains. A problem of poor frequency response was linked to the liquid electrolytes. When glycol borate was used on germanium a thin green film was forming. Recognizing this as germanium dioxide, an insulator, they figured they could put an electrode on the film to control the current. Gibney prepared a new slab of germanium with a shimmering green oxide layer on one surface and several small spots of gold on the oxide. The water soluble film was accidentally washed away before the gold dots were placed and the experiment didn't work as expected since the dots were not insulated from the germanium, but they serendipitously discovered a new phenomenon instead. Brattain chanced to apply a positive voltage to a gold spot and a negative voltage to a point-contact placed at its edge. He got some modulation with no power gain, but a doubling of voltage gain independent of frequency to 10kHz. This led them to theorize that putting two closely spaced point contacts on germanium would yield good results. Brattain figured out how to space two contacts 2 mils apart and on December 16th, 1947 they were ready to test it. The results were marvelous with high power gains and no frequency degradation. The solid-state amplifier, using a primitive point-contact form of a bipolar transistor, was born!



On December 23rd, 1947 with just a tiny slab of germanium, a thin plastic wedge for a mount and a couple strips of gold foil, they amplified an electrical signal almost a hundredfold! Besides the three fathers, two executives were present for the demonstration. Without tubes, Brattain's voice spoken into a microphone was amplified loudly in a headphone. Both executives shook their heads in wonder, but the apparatus had a long way to go in reliability and reproducibility before it could replace vacuum tubes. One executive asked: "Can it oscillate?" and on Christmas eve Bardeen and Brittain demonstrated that a piece of germanium could oscillate. Immediately the invention went into secrecy.

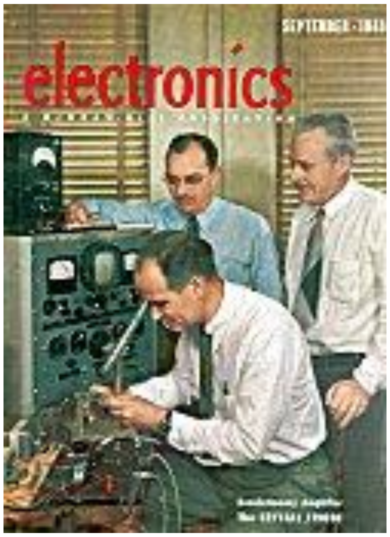
It was well known that Purdue University was also working on semiconductors, but their research was open to the public. Shortly after the demonstration Shockley found that Bardeen and Brattain were consulting with patent attorney Harry Hart. As group leader, Shockley wanted to write a patent starting with the field-effect and then the rest. Unfortunately, prior art was discovered on patent 1745175 issued in 1930 to a German physicist named **Julius Lilienfeld** for a field-effect device. It was evident that Shockley's field-effect idea was not original and so the patent had to be based on Bardeen and Brattain's work which was clearly original. Having not been one of the inventors, Shockley was chagrined to have no direct role in this crucial breakthrough even though his efforts began eight years before. Not only had his field-effect idea been anticipated two decades earlier, but also the patent attorneys refused to include his name on the patents for the solid-state amplifier. With this, a wedge was driven into the semiconductor group. Now nearly every moment he spent trying to design a better solid-state amplifier that could be manufactured and used more easily. In 1948 he had solutions. His idea was use nothing but a strip of semiconductor material, either silicon or germanium, with wires attached at "junctions" at the ends and middle rather than the delicate and unpredictable "point contacts" made by Bardeen's and Brattain's device and used in early crystal radio detectors. The semiconductor material would form a compact and reliable layered P-N-P device. Later he realized that an N-P-N layered device, produced by evaporation and with a directly contacted thin base, would be even more efficient. Shockley was secretive about his conception of the bipolar junction transistor (BJT), which would soon drive the commercialization of the transistor radio.

In 1948 the point-contact transistor was independently invented by two German physicists working in Paris**. Herbert Mataré** developed crystal rectifiers from silicon and germanium at the Telefunken laboratories in Berlin, while **Heinrich Welker** worked on purifying germanium in Munich. After the war ended they were hired by the Compagnie des Freins et Signaux, a Westinghouse subsidiary, to develop and manufacture solid-state rectifiers from these materials. In 1947 Mataré began researching an odd phenomenon called "interference" that he had witnessed in germanium rectifiers during the War. If two point contacts were sufficiently closely spaced, within 100 micrometers of each other, the potential on one of them could influence the current flowing through the other like seen at Bell Labs. Early the next year Mataré achieved sporadic amplification of electrical signals. By June 1948 he obtained consistent, reproducible results using higher-purity samples of germanium produced by Welker. A month later they learned the surprising news that Bell Labs had just invented a similar semiconductor amplifier. The company rushed to get its "transistron" into production. By mid-1949, thousands of them were being manufactured for use as amplifiers in the French telephone system. These primitive point-contact devices were soon superseded by the superior junction transistor.

Back at Bell Labs, physicist **John Shrive** began work on a bipolar transistor configuration suitable for encapsulating into a rugged and compact cartridge with leads. He ground down a sliver of N-type germanium to a thin taper and on both sides of the 2 mil thick end, point contacts were placed. The fact that it worked was puzzling to him because in the past they had used thin surface layers of opposite type over the semiconductor, but not here. Shockley was startled when Shrive presented his findings at a meeting. It showed that his secretly held layered idea would work. Shockley knew that Bardeen would immediately reach the same conclusion, possibly in the next few minutes, so he jumped up and presented his ideas to interpret the findings that holes could diffuse through bulk germanium in the presence of a much larger population of electrons or vice versa. This surprise revelation encouraged patents to be filed quickly. On February 26th, 1948 three patents for Bardeen and Brattain's use of electrolytes and point-contact devices were filed. A rift had widened between Bardeen and Brattain with their working point-contact amplifier and Shockley with his layered approach still in development. Shockley had strong convictions that his layered junction idea would win out and he reminded his subordinates, Bardeen and Brattain, so. Shockley felt he could devise all theoretical ideas himself. The Bell Labs brass was placing its bets on him. The free sharing of ideas with no concern over patents was gone. Bardeen developed equations relating currents and voltages from which gains in performance were made in the point-contact device. Shockley had obtained similar conclusions, but by using more complex differential equations.

Meanwhile **Bill Pfann** developed a cartridge device that enclosed the point-contact amplifier. Dubbed the "Type A", it was a 0.75" long by 0.25" metal cylinder that had two fine wires pressed onto an internally mounted slender chip of germanium. The wires connected to the emitter and collector. The base was connected to the cylinder. Although noisy, the power gain was good and their electrical characteristics were stable and reliable enough to be designed into new products. Bell scientists perfected techniques to grow usable germanium crystals for mass production and by June Bell engineers designed the point-contact transistor into new telephone equipment such as repeaters and a radio receiver. Scientific papers were being prepared for the nearing public announcement. Now a proper and enduring name for the device was needed. Names such as "semiconductor triode", "surface states amplifier", "crystal triode" and "iotatron" were considered by a committee. Finally, based on its perceived operation of trans-resistance, the name "transistor" was overwhelmingly approved.

The new invention was announced June 23rd, 1948 in secrecy to the military where the Bell staff were told that the Naval Research Lab had made similar discoveries and wanted a joint public announcement. After Shockley asked them some technical questions it was determined that they had no data which showed power gain and probably wouldn't get any. The military was given a few days to determine if they wanted the invention kept secret or jointly announced, but never requested either. Bardeen and Brattain prepared papers to be published in the July 15th issue of "Physical Review". Then, on June 30th, 1948 it was publicly announced at a Bell Labs press conference. "We have called it the Transistor because it is a resistor or semiconductor device which can amplify electrical signals as they are transferred through it". They held up the cylindrical type "A" transistor, made comparisons to vacuum tubes, and declared it could handle up to 100mW of power and operate to 10MHz. Through headphones the reporters could listen to presenter's voices and radio stations amplified and detected by only the transistor. Although the reporter's present gasped during the demonstrations, the press paid little attention to it, not knowing that the unremarkable little cylinder with flimsy wires would ultimately transform the world. The revolution it created in communications, computing and miniaturization continues unabated today. A more technical presentation was held July 20th. Lee de Forest was an invitee, but he refused stating that he could not attend "the Wake of my forty-two year old infant, the Audion", his vacuum tube amplifier invention. Technical publications on the Transistor were very popular where it was declared to have far-reaching effects on technology. September's 1948 "Electronics" magazine's cover showed Shockley working at a laboratory workbench with Bardeen and Brattain (right) idly standing behind him watching. The July 15th issue of Physical Review printed three letters, two by Brattain and Bardeen and a third by Shockley and Pearson. In fall all three hit the scientific and engineering lecture circuits across the nation. Shockley then turned his attention to classic writings on the theory of P-N junctions and on patent applications. His intellectual output was phenomenal.



The cartridge “Type A” transistor was not ready to hit the market in late 1948, but samples were given to military and university researchers and sent to GE, Motorola, RCA and Westinghouse under licensing agreements. No two transistors behaved the same and they were electrically noisy. Advances in pure single crystal growth, needed to produce semiconductors with easily controllable and uniform properties, were made by starting with “seed” crystals. The seed crystal growth was based on work in 1917 by Polish scientist **J. Czochralski** whose technique was to place the seed in contact with a molten liquid while slowly withdrawing it as uniform layers of atoms accumulated on its lower end. Work went on at Bell by physical chemist **Morgan Sparks** to replace the troublesome and noisy point contacts with P-N junctions. Sparks considered Shockley to have tremendous insights into materials as well as being a brilliant lecturer. He later became president of Sandia Laboratories (national lab managed by AT&T). Meanwhile, RCA and other research labs tried developing similar metallic amplifiers that did not infringe on existing patents. In 1950 Sparks fabricated a single crystal N-P-N sandwich by applying P-type “pills” of gallium (base) to N-type germanium (collector) to form a P-N junction and then an N-type pill of antimony (emitter) on top the P to form an N island inside the P. This first NPN sandwich had poor frequency response compared to point contacts because of the large 20-30 mil thickness of the P base region. This same year Bardeen’s and Brattain’s point-contact transistor patent 2524035 was approved. By 1951 the P-layer was reduced to 1-2 mils and frequency response was improved. Soon after, pea sized germanium junction transistors were developed that were more efficient and vastly less noisy than point-contact transistors, allowing much weaker signals to be amplified.

Shockley advised military ordinance officers on the use of the new junction transistor in weapons. Another first, Shockley devised a demonstration consisting of a wireless transmitter and microphone that he walked around with while giving presentations. In 1951 Shockley was elected a member of the prestigious National Academy of Sciences. Bardeen subsequently left Bell Labs for a university where he could perform pure research and Brattain quietly got himself reassigned elsewhere within the Labs. Bardeen wrote to his supervisor “My difficulties stem from the invention of the transistor. Before that there was an excellent research atmosphere here”. The three would meet again briefly in Stockholm in 1956 to share the Nobel Prize in physics for their invention of the transistor.

On July 4th of 1951 Bell Labs held another press conference to show the junction transistor. The spidery, pea-sized device was called “a radically new type of transistor that has astonishing properties never before achieved in any amplifying device”. It could operate highly efficiently consuming just 10 micro-watts of power where a vacuum tube would require 100,000 times more power and the point-contact transistor 200 times more power. Its supreme efficiency was a great advantage for the newly emerging digital computers. Also announced was that the point-contact transistor, produced at Western Electric, was ready to be put into trial use in the Bell System’s switching equipment the following year. The point-contact transistor never made it big in the commercial market due to the superior junction transistor.

After Shockley’s junction transistor patent 2502488 was issued in late 1951, Western Electric began licensing the rights to manufacturing it for a $25K down payment on 5% royalties. It was hoped that sharing the technology with other companies would spur development of electronic devices that the telephone company could use. The art of fabrication was not a secret much longer. In early 1952 licensed companies sent representatives from 26 U.S. and 14 foreign companies (all NATO) to attend the Transistor Technology Symposium. Everything known about the point-contact and junction transistors was revealed including a new method of obtaining 99.99999999 % pure germanium by a process called zone refining. Texas Instruments (TI) was reluctantly licensed after convincing Western Electric lawyers that it could develop competence to compete in the field. Raytheon and GE signed up too. Nascent Sony, named Tokyo Telecommunications at the time, was barely able to spend the $25K that represented 10% of its worth. Hitachi, Mitsubishi and Toshiba had signed up as well.

In 1951 GE fabricated a PNP transistor using alloy-junction techniques where two small pellets of indium are placed on opposite sides of a thin slice of N-type germanium and heated to 840F, until just short of dissolving all the way through, leaving a narrow base. Although cruder than junction types, their low resistance was superior for switching applications in digital computers. In 1946 engineers at the University of Pennsylvania had built the first large digital computer dubbed ENIAC (Electronic Numerical Integrator and Computer). Weighing in at 30 tons with 18,000 vacuum tubes consuming 150 kW in a 30' x 50' room, it performed calculations for ballistic tables. Bushel baskets of spare tubes were always on hand. In 1949 on GE's radio program Science Forum, Shockley had prophesized the use of transistors for electronic brains. An early military application for transistors was in data transmitters that took target coordinates from radar and converted the data to binary form for transmission over phone lines to a control center for display on a CRT video display. In 1954 a transistorized general-purpose computer for the Air Force called TRADIC (TRAnsistorized DIgital Computer) was built by Bell Labs. It used 684 of its 1734 Type A cartridge point-contact transistors at $20 apiece along with 10,358 germanium point-contact diodes. Because 30 watts of power output was needed for the 1 MHz clock, a single vacuum tube was needed at the time to buffer the clock. Programs were introduced via a removable plugboard, while the flyable B-52 bomber version used a Mylar sheet with punched holes.

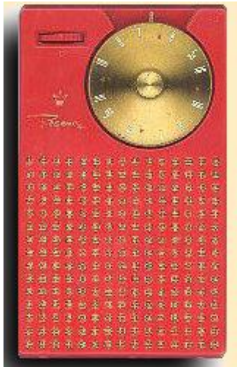
From 1953 to 1955 almost half the funding for transistor development came from the military. In 1953 the Signal Corps underwrote construction costs of a Western Electric plant and spent millions on production lines at GE, RCA, Raytheon and Sylvania as well. After the Korean War ended the quartz crystal market was falling off a cliff. However by 1954, General Transistor was producing transistors for Remington Rand's Univac division that was an early manufacturer of computers using transistors. When **Seymour Cray** and **Bill Norris** left Univac to found Control Data Corporation (CDC), General Transistor designed the higher speed germanium drift transistor for the CDC 1604, the world's first large scale fully transistorized computer. A new industry was born!

Transistors were an important component to AT&T's direct dialing system, repeater circuits for rural areas that could derive their operating power over the telephone lines and the hearing impaired. In 1952 Sonotone began replacing the three vacuum tubes in their hearing aids with a junction transistor. Bardeen's wife used one of the first transistorized hearing aids. Raytheon, also in the hearing aid business, was the largest manufacturer of transistors in the world between 1952 and 1955. It replaced three or four hearing aid tubes with as many transistors. In 1953 Raytheon loaned Bell Labs 500 transistors because Bell had only 300 working transistors and its 500 engineers needed one each! Raytheon was producing 10,000 a day by then. A 1953 Fortune Magazine article titled "The Year of the Transistor" proclaimed "In the transistor and the new solid-state electronics, man may hope to find a brain to match atomic energy's muscle".

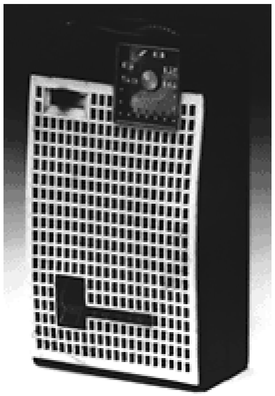
In the early 1950s **Lyda Teal** at Bell Labs was concentrating on the nearly insurmountable task of growing and doping large silicon crystals. The melting point of silicon is 1410C instead of the 937C of germanium and is more reactive with almost any crucible. Even the best quartz containers slowly dissolve in the melt. But silicon is the Earth's second must abundant element and has preferable electrical properties. Germanium's main limitation is that performance degrades greatly with increasing temperature because its electrons can too easily break free for conduction with thermal energy. Teal left Bell for TI where he continued work on silicon. Finally in 1954, using $500 per pound silicon from du Pont, he grew a working NPN junction device. This was a defining moment for TI and it raced to set up production before other companies had a similar breakthrough. The device was publicly announced at a conference where one after another presenter remarked how hopeless it was to expect development of a silicon transistor. By the time Teal began the audience was drowsy and many began to nod off as he droned on monotonously. Finally he proclaimed "Contrary to what my colleagues have told you about the bleak prospects for silicon transistors, I happen to have a few of them in my pocket". The audience suddenly woke up and was further told that TI had three types in production. Teal then demonstrated a phonograph amplifier with germanium transistors dunked into a hot beaker of oil until it failed to operate. When a silicon-based amplifier was substituted the audio continued without interruption. They initially sold for hundreds of dollars apiece, mostly to the military.

1954-1955: Commercialization of the Transistor Radio

With the end of the Korean War TI's military business was faltering and a boost in income was needed from the commercial arena. TI was convinced that an all transistor pocket radio was feasible, but RCA and others preferred to stick with vacuum tubes and had a wait and see attitude towards the transistor. Amateurs used transistors to design experimental radio circuits as early as 1950 and Western Electric engineers made a wrist radio in 1952 with 4 transistors as a gift for Dick Tracy creator Chester Gould. In June 1954 TI finally reached agreement with a small Indianapolis company named Regency to design and manufacture the first commercial transistor radio for the Christmas market. To keep cost down it was designed to use four junction germanium transistors that had to come in at $2.50 apiece with the remaining parts at $18 for a profitable sales price of $50. Normally the transistors were $16 apiece, but expected high production and increasing yields from 10% would drop the price. Workers grew doped germanium crystals sawed into tiny bars. Each bar was etched and polished then three wires attached. After testing and rejecting most of every lot they affixed capacitors to those that passed to compensate for variability and then encapsulated them. TI also designed and built the compact circuitry. They found companies that supplied the tiny speakers, coils and other components on short notice. Regency's master engineer**, Dick Koch**, designed a feedback circuit that accommodated the tolerance of components and let them be soldered directly into the boards without manual selection. The TR-1 utilized a 22.5V battery that ran for over 20 hours and was only 3"x5"x1.25" in size.



Fortunately everything came together and Regency's TR-1 pocket radio began production on schedule in October. Despite a major promotional campaign Regency only shipped 1500 radios by the end of 1954, but surged to 100K by late 1955. It sold out quickly, but at $50 the radio was under priced for demand and was not profitable because the transistor price goal wasn't met. TI became the principal transistor supplier to Admiral, Motorola, RCA and Zenith after it had shown them the way. The transistor radio finally brought the public's attention to the tiny and esoteric transistor. Mention the word "transistor" to owners of these early radios and images of them instantly come to mind. In 1955 IBM bought over a hundred TR-1s to give to its top executives telling them "If that little outfit down in Texas can make these radios work for that kind of money, they can make transistors that will make our computers work too." Two years later TI agreed to provide transistors for IBM's first fully transistorized computer.



While TI and Regency were designing their TR-1, Sony was developing its TR-52 junction transistor radio. It was nicknamed the "UN Building" by its engineers because the black plastic case with a white plastic grid on the front tapered slightly at the top. It was meant to be the first transistor radio on the market, but was beat to the finish by the TR-1. In 1955 Sony approached Raytheon and offered 20% of the company in return for Raytheon teaching Sony how to build transistors. Knowing that Japan's labor rates were one-seventh that of the U.S. Raytheon declined, but Sony had attended the 1952 Transistor Technology Symposium. Early in the year watch maker Bulova wanted to order 100K units of the TR-52, but the catch was that they would sell them under their name because at the time nobody had heard of the "Sony" name. Sony refused the order. Soon disaster struck. As summer temperatures climbed, the front lattice section gradually peeled away from the black cabinet on all of the 100 sets manufactured so far. The radios were unsaleable**.** In August that year the remodeled 5-transistor model TR-55 (below L) went on sale. During radio construction transistors which were slow to operate would be paired with coils to improve their performance. It had the honor of being Japan's first transistor radio. It was followed the same year by the 6-transistor TR-72 (below R), with a push-pull amplifier for improved sound, which continued to be a popular radio into the 1960s. Transistor radios became a status symbol for teenagers who owned one. Other U.S. companies introduced dozens of transistor radio models and by 1959 almost half of the 10 million radios made and sold in the U.S. were the portable transistor type.

The first transistor radios could not receive FM because the frequency of around 100MHz was too high for the transistors of 1955 that could reach only 20MHz at best. To better the frequency range the transistor's base had to be made thinner than 1 mil and the area of the base needed to be made smaller to decrease unwanted capacitance. To achieve these goals a "diffused-base" junction transistor was under development that was enabled by ultrapure single crystals of germanium and silicon to which precisely controlled amounts of foreign atoms could be added in an ultraclean environment to form tiny N and P type regions. At Bell Labs **Ian Ross** demonstrated that his epitaxial process could be used to solve the problem of reliably fabricating a thin base by growing a thin single crystal layer of lightly doped material on top of a heavily doped material and diffusing an emitter into it. Atomic diffusion was a powerful method of controlling the addition of foreign atoms by carefully adjusting the density, pressure and temperature of a vapor of those atoms for a predetermined density and depth (0.1 mil). Any foreign substance in the vapor would diffuse into the crystal as well and poison the results. In the mid 1950s such poison was dubbed "deathnium" by Shockley and others until it was discovered to be copper unwittingly transferred from door knobs to crystal surfaces by technicians. By late 1954 the first transistor using diffusion was achieved. A PNP diffused base germanium transistor had amplified signals up to 170 MHz., nearly 10 times better than the previous best. Broad patents were filed for diffused transistors by Bell Labs with Shockley as one of the inventors.

Fabricating a silicon based diffused transistor took a few months longer because the very hot gases used often scarred the silicon surface to a point where it looked like cinders pulled from a fireplace. Silicon had to be processed at a daunting 2700F (1300C) which resulted in pitted and scared surfaces, but one day in early 1955 chemist **Carl Frosch** accidentally ignited hydrogen gas and introduced water vapor into the diffusion chamber. Until that moment he had avoided this for fear the oxygen in the water vapor would oxidize the silicon wafers, but serendipity struck again. The oxide formed a protective coating on the silicon surface that kept it from pitting and charring. In early 1955, **Morris Tanenbaum** of Shockley's group succeeded in making their first diffused-base transistor. This NPN transistor was crude in appearance yet advanced in performance, operating at 120 MHz. From here it was established that diffused silicon would be the technology for future transistor and diode development at Bell Labs. Support for all other prior transistor technology was abandoned. Bell Labs went public with the diffused silicon transistor in mid 1955 and held a symposium for licensees, but transistor manufacturers were satisfied with the cheaper and easier to produce alloy-junction transistors they had for use in hearing aids and transistor radios. Fortunately, Bell and Western Electric had wealthy customers that included the U.S. military and AT&T. All were interested in the highest frequency performance possible where information could be transferred most rapidly and they would readily provide funding for the high up-front costs of manufacturing and the $100 piece price for the transistors. The U.S. Air Force used Bell's expertise to help build the DEW (Distant Early Warning) Line consisting of 50 early-warning radar stations spread across the northern reaches of the continent.

In early 1954 Bell Labs announced its Solar Battery that was readily accepted by the general public. It made news everywhere including the front page of the "Times" whose headline proclaimed "Vast Power of the Sun is Tapped by Battery Using Sand Ingredients" and "Beams of light have also provided electricity for a transistor in a radio transmitter, which carried both speech and music". Philco introduced the first transistor TV in 1959, but after Sony began manufacturing transistor TV sets in the 1960s U.S. leadership in consumer electronics began to wane.

It was Bell Labs again that in 1960 made the breakthrough for the field-effect transistor that is used widely today in most integrated circuits (ICs). The solution was a glassy oxide layer deposited on its surface after a careful cleaning that drastically reduced the surface states caused by contaminants and dangling molecular bonds. With the surface states nearly eliminated, applied external electric fields could penetrate into the silicon and modulate its conductivity. If Bardeen and Brattain had been working with silicon instead of germanium in 1947 when they accidentally washed away the germanium's oxide they would have stumbled across the field-effect transistor instead of the point-contact transistor!

1955-1960: All Ions Wind up in California

Shockley had reached a glass ceiling at Bell as head of the transistors physics department. With his overbearing competitiveness and hamhanded approach to dealing with people, Bell felt he was where he would be most effective. Yet he was not granted any share of royalties accruing from his patents even as his honors and awards piled up. He began to seek in other directions for his own fortune and interests. He spent some time teaching at Cal Tech, but he soon found that the personal satisfaction and sense of fulfillment he sought was not to be found in academia. In 1948 he helped set up the Weapons Systems Evaluation Group for the evaluation of strategic weapons, but refused a leading role so he could continue transistor research. By late 1954 he became disinterested in the work because it was an advisory group without real authority. For almost a year he had considered positions at various companies and universities and was awaiting an outstanding offer, but by early 1955 decided to devote his efforts to starting his own company. He sought to raise $1 million. Raytheon showed interest, but they couldn't agree on terms for him to set up a lab. Finally, a company named Beckman Instruments agreed with the terms, "We propose to engage promptly and vigorously in activities related to semiconductors. The initial project contemplated is the development of automatic means for production of diffused-base-transistors." Shockley proposed the San Francisco Bay area to be near Stanford University. To build the company Shockley tried to raid Bell Labs for talent, but was unsuccessful as no one wanted to uproot their families to move across the U.S. He did succeed at recruiting talent from Motorola, Philco, Raytheon and Sylvania as well as from top schools such as Berkeley, Cal Tech and MIT.

The first facility for Shockley Semiconductor Laboratory in early 1956 was a leased Quonset hut at 391 South San Antonio Road. It looked more like an auto parts store than the headquarters of a new high-tech company, but was adequate until a new facility was built at the nearby Stanford Industrial Park. This area was known as "The Valley of Heart's Delight" for the fruits that flourished there. One name that cropped up repeatedly while recruiting was physicist **Robert Noyce**. Noyce later recalled the first contact from Shockley "It was like picking up the phone and talking to God. He was absolutely the most important person in semiconductor electronics". Noyce had a fascination for the west coast and said "All ions wind up in California, if they meet their dream." Noyce was hired after successfully completing a number of psychological tests to see if he would fit into the group. Another key hire was **Gordon Moore**, a physical chemist. Shockley fired a quick series of questions to Moore, timing his answers with a stopwatch. By June the company had more than twenty employees. Even though Beckman had obtained rights to proprietary processes from Bell Labs the first year proved difficult, yielding only P-N junction diodes. The ultrahigh-technology environment of Bell Labs was not easily replicated across the country and the planned move into the new facility kept getting put off.

On November 1st, 1956 at 7:15AM, Shockley received news that would change his life. Together with John Bardeen and Walter Brattain, he had won the Nobel Prize in physics for the invention of the transistor. Phone calls flooded in and the press swarmed around him shoving cameras and microphones at him. The actual ceremony took place December 10th, the sixtieth anniversary of Alfred Nobel's death. The three winners got along splendidly for the occasion as if no tensions ever existed.

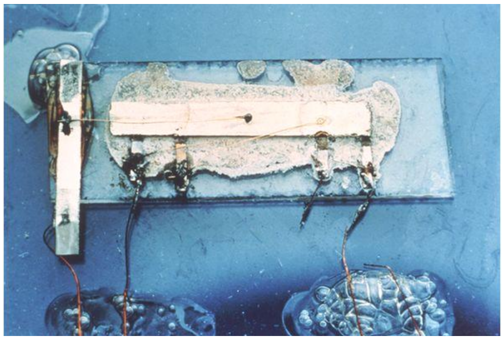
After a year Shockley’s company was still months away from production and not on plan to be making thousands of transistors a week. His top employees were beginning to grumble and defect and there was a general feeling of resentment of his heavy handed management style amongst them. As things worsened Shockley reacted with suspicion and tensions between him and Beckman increased. Manufacturing silicon diffused-base transistors no longer seemed important to Shockley. He was instead interested in difficult cutting edge projects such as the P-N-P-N diode, also known as the “Shockley Diode”, which he had conceived at Bell. Beckman met with Shockley and his dissidents to forge a plan whereby Shockley remained in control of the company as president, but everyone else would report to a manager. The search for the manager was headed by Noyce. Shockley continued his Shockley Diode work with several loyalists at the Spinco building where space and utilities were available. Despite the new plans the truce was uneasy and the factions drifted apart, but the Shockley Diode did enter production. By September of 1957 eight of Shockley’s brightest, including Noyce and Moore, had defected causing the company to become nearly totally ineffective. Fairchild Camera and Instruments agreed to fund the dissidents with $1.3 million to form their own company just one day after their resignation. Fairchild Semiconductor was led by Noyce in a leased building about a mile north of the Quonset hut along San Antonio Road. Their goal was to produce high frequency diffused transistors. A month later Sputnik was orbiting overhead. As the space age began, the U.S. rushed to close the missile gap and semiconductor companies found an exploding ready to pay military market for their tiny, flea weight and low power consumption replacement for vacuum tubes. As many other semiconductor companies began to sprout, this area of the country came to be known as “Silicon Valley”.

In 1958 Shockley’s renamed company, “Shockley Transistor Corporation”, could manufacture hundreds of four-layer diodes, but they suffered wide variation in performance. Samples were sent to Bell Labs hoping AT&T would purchase large quantities for electronic switching systems, but their conservative engineering couldn’t tolerate the variations. The difficulty in manufacturing these diodes was that impurities had to be precisely diffused into both sides of a paper thin slice of silicon. Noyce, Moore and other dissidents had rejected this project and wanted to manufacture three layer transistors that required diffusion on only one side. Within a year Fairchild was manufacturing transistors using techniques learned at the Quonset hut. Shockley’s irrational fascination of the four-layer diode was implanted into his brain several decades earlier by Kelly. Shockley stated at the 1958 Brussels World Fair: “Such diodes can be made to amplify digital signals … they may prove economical to manufacture…”. With assistance from new employees easily obtained with help of his world fame, Shockley’s company worked on another of his ideas, the field-effect transistor that he conceived in 1945. These efforts met with little success and Shockley refused to make simpler devices. He felt he just didn’t have the right people. Fairchild also lost personal when its head of production and seven others defected to form another semiconductor company just a few blocks away. Along with them went proprietary information. Beckman watched the exodus of the intellectual capital that he had spent over a million dollars on at Shockley Transistor Corporation while Fairchild was grossing millions of dollars. He began negotiations to sell it off after he finally accepted that despite Shockley's brilliance, he could not operate a profitable business. Instead, he was running an R&D operation and training future leaders of the emerging industry. This was of great importance to fueling the revolution for this nascent industry, but for the first time Beckman had experienced an operating deficit. Shockley began to admit that he had difficulty with Ph.D. scientists and engineers he hired from the U.S. so he decided to recruit a new crop from Germany where Ph.D.’s had a master-slave relationship with their thesis professors. In April of 1960 Clevite Transistor company of Massachusetts purchased Shockley Transistor Corporation for an undisclosed amount, but acknowledged an expected $400K loss for the remaining year. In 1963 Clevite closed the Silicon Valley operation and moved production to Waltham, MA.

1958-1961: The Monolithic Idea

By 1957 U.S. production had become 30 million transistors per year with average unit cost of a few dollars apiece. The growing reliability and uniformity of transistors were replacing vacuum tubes in even the most complex circuits such as digital computers and telephone switching systems. But as components of these systems swelled into the thousands the number of interconnections, usually made by hand, was exploding. Chances of a wiring fault became high with this "tyranny of numbers" as it was called. The military sought to make connections reliable and thus printed circuit boards became common in the 1950s. Visionary engineers began looking for other ways to eliminate individual components and interconnecting leads entirely. This effort led to what has become commonly known as the "monolithic integrated circuit" and "Molecular Electronics" by the Air Force. Efforts were made by RCA, Westinghouse and other U.S. companies usually by contract with the military, but a decade after the transistor's birth the IC remained just an idea.

While at the Centralab division of Globe Union during the war, **Jack Kilby** had worked with silkscreen methods to print thick film resistor and capacitor circuits for proximity fuzzes on ceramic. Post-war the technique was used on some radio and television circuits. In 1952 Globe Union purchased a patent license and sent Kilby to Bell's second transistor symposium. Upon return he developed a hearing aid that combined silkscreen and four transistors that was featured on the front cover of October 1956 Electronics magazine. Recognizing the future was in silicon, he attended the third symposium in 1956. Realizing that Centralab could not afford to build its own semiconductor factory he found a job at TI in early 1958 working on the Army's Micro-Module program. Individual components and printed circuits were fabricated on tiny square wafers packed side by side. During a two week shutdown of the TI plant Kilby sought to improve upon the kludge and overcome the tyranny of numbers. On July 24 in 1958 Kilby realized that "Extreme miniaturization of many electrical circuits could be achieved by making resistors, capacitors and transistors & diodes on a single slice of silicon." He showed how to do this on five notebook pages. He later said "Nobody would have made these components out of semiconductor material then. It didn't make very good resistors or capacitors, and semiconductor materials were considered incredibly expensive." But doing so would make monolithic integration possible by using familiar semiconductor techniques and batch processing to reduce cost. With single transistor yields of 10% and much higher quality resistors and capacitors made from other less expensive materials, TI officials were skeptical about Kilby's ideas until he could demonstrate a working IC. Having worked through his ideas, Kilby fabricated a proof of concept oscillator from several germanium pieces to fabricate the transistor, resistor and capacitor needed and then connected them with fine wires. It was crude, but on September 12th power was applied and a few witnesses saw the green wavy line on the oscilloscope indicating an oscillation at more than 1 MHz. A week later Kilby demonstrated an integrated flip-flop using two transistors. Having proved that integrated circuits could be built, Kilby's "monolithic idea" became a reality.



Kilby then concentrated on adapting printing industry photolithography first to germanium, then silicon, to define areas on the semiconductor surface. This allowed those areas to be masked out for etching or adding materials through vapor deposition to form circuit elements. In January of 1959 a rumor reached TI that RCA was about to file a patent on integrated circuits. Terror stricken TI lawyers quickly assembled a hasty patent application in Kilby's name. Nine days later a broad based patent application for "Miniaturized Electronic Elements" was filed. A month later TI announced its "Solid Circuit" at the Institute of Radio Engineers show. About the size of a pencil point, its flip-flop performed as well as circuits a hundred times bigger. As it turned out it was Fairchild instead of RCA that needed to be worried about.

Fairchild was set up at 844 East Charleston Road, about a mile from Shockley's lab, with Noyce as head of research and Moore leading production engineering. Moore developed the 2N967 NPN transistor for IBM's magnetic core memory drivers. By the fall of 1958 Fairchild sold diffused base transistors to IBM for $150 apiece. By December they had $500,000 in revenue and a profit to boot. The "mesa" technique invented at Bell etched away selected layers and left mesas to which two wires were attached with a third wire to the bottom layer for electrical connection. But this left exposed P-N junctions between strata which were easily contaminated and limited yields of good devices. Physicist **Jean Hoerni** of Fairchild developed a "planar" process whereby a protective layer of silicon dioxide, an excellent and resilient insulator, coated the device. Holes could then be etched through the oxide to make electrical contact with narrow metal wiring lines running atop the oxide. Combined with photolithography, fine patterns smaller than 1 mil across could be obtained and new possibilities achieved. While Kilby concentrated on fabricating various circuit components Noyce focused on batch processing their electrical connections to avoid tedious manual labor. Fairchild initiated a project to build prototype "unitary circuits" while Noyce and his attorney wrote a patent application titled "Semiconductor Device and Lead Structure" for the planer process and method of interconnection between circuit elements.

In April of 1961 the U.S. Patent Office awarded the first patent, 2981877, for an integrated circuit to Noyce, not Kilby. Fairchild's narrower application raced through the approval process. Kilby's application was still plodding along as examiners raised petty objections that had to be addressed. In the meantime engineers rushed to bring products to market. Fairchild barely won the race by solving the last problem of how to mask the silicon wafer for successive and precisely aligned photolithography steps. In March of 1961 Fairchild introduced six compatible Micrologic Elements and sold them to NASA and OEMs for $120 each. In October TI released its Series 51 Solid Circuits, containing two dozen transistors, diodes and resistors, at lower prices than Fairchild. It also demonstrated a midget computer made of 587 Solid Circuits the size of a sardine can and that weighed only 10 ounces. It had the processing power of a conventional computer at the time yet was 1/150 the size and 1/50 the weight. In about 15 years computers had shrunk from a roomful of power hungry equipment to a small handheld box. Business Week magazine said that semiconductors "make it possible to design and build computers with the logical capacity of the human brain".

In May of 1961 President Kennedy had overnight created a critical market for ICs when he announced that the U.S. should put a man on the moon by the end of the decade. It took the Apollo moon and MinuteMan missile programs in the 1960s to establish integrated circuit technology as the technology of choice. Integrated circuits would be used in nearly all spacecraft systems to greatly reduce size, weight, power consumption and increase reliability.

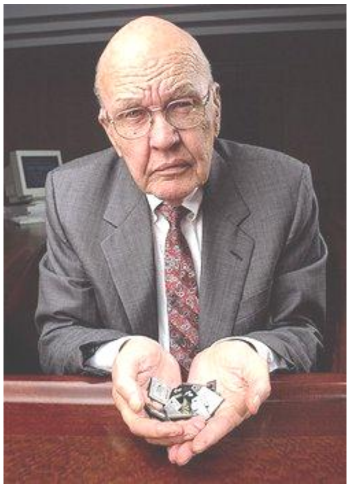
Epilogue:

The nascent semiconductor industry was growing convulsively and after a pause in 1961, due to a price war and drop in military orders, gross sales passed the billion-dollar mark. The industry was the fastest growing in the world. This new technology changed the way product development was done. Before, there were the basic component manufacturers and the separate system design and assembly companies, but these were becoming somewhat consolidated as ICs took on more complex and varied functions. On the other hand ICs allowed design and assembly companies to conceive products of ever greater complexity. Silicon diffusion technologies were mastered by companies in the Sun Belt states of California, Texas and Arizona. Others in the Northeast who stayed with germanium and alloy junctions soon faded away. Transitron Electronic Corporation in Massachusetts began producing silicon transistors in 1957 and later a broad range of transistors, ICs and high reliability military products.

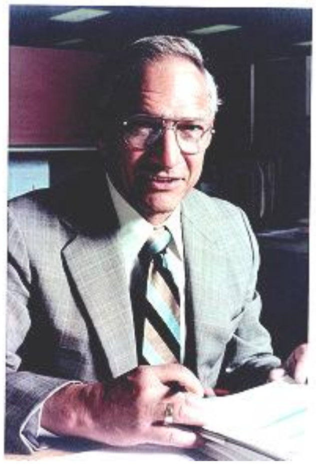
Despite Shockley's immense contributions he never became the millionaire he longed to be. The entrepreneurial spirit that began with the defections from Shockley Semiconductor Laboratory multiplied a hundredfold as job-hopping and piracy of trade secrets became common. Many others turned silicon into gold and made themselves millionaires and billionaires. Shockley never got to enter the promised land himself. His long time friend Fred Seitz called him "The Moses of Silicon Valley".

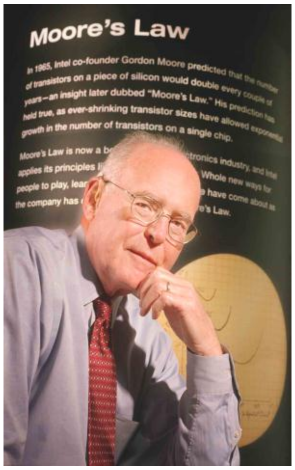
Bardeen continued doing basic research in solid-state physics and superconductivity while Brattain researched surface phenomena. Both avoided long and arduous development. Bardeen taught semiconductor courses in Urbana at the University of Illinois. His work on superconductivity, which for decades resisted theoretical attempts to explain it, resulted in a pivotal article titled "Theory of Superconductivity". He was awarded a second Nobel Prize in physics for this work in 1972 and became the first to earn two Nobel Prizes in the same field. He also consulted for General Electric and Xerox and from 1959-1962 was a member of the President's Science Advisory Committee under Eisenhower and Kennedy. He resigned under President Reagan when Reagan decided to proceed with "Star Wars".

Brattain realized the impact of the invention in the early 1960s when he visited Egypt and saw a camel rider listening to a transistor radio. He realized anyone in the world could listen to news from the U.S. Brattain retired from Bell in 1967, moved back to Walla Walla and spent his remaining years at the college working on biophysics and teaching physics.



Kilby's development of what became known as "The Monolithic Idea", whereby various types of circuit elements could be included on a single semiconductor chip, led to his Nobel Prize in Physics in 2000. In his usual humble mood he said "Humankind eventually would have solved the matter, but I had the fortunate experience of being the first person with the right idea and the right resources available at the right time in history." During his Nobel acceptance speech in Stockholm he went out of his way to credit Robert Noyce by saying "I would like to mention another right person at the right time, namely Robert Noyce, a contemporary of mine who worked at Fairchild Semiconductor. While Robert and I followed our own paths, we worked hard together to achieve commercial acceptance for integrated circuits. If he were still living, I have no doubt we would have shared this prize." Kilby was awarded patent 3138743 in June of 1964 for his first IC. After proving that integrated circuits were possible he headed teams that built the first military systems and the first computer incorporating integrated circuits. He also worked on teams that invented the handheld calculator and the thermal printer. During his career he became known as "the gentle giant" because he was soft spoken and tall. Although fame eluded him his entire life, his peers recognized his achievement nearly instantly and over the years awarded him nearly every prize they had to offer.





Noyce and Moore became disenchanted with Fairchild. While it was a great inventor, developer and marketer, it was slow to get a product successfully into manufacturing. They resigned in 1968 and started a company whose name was derived from Integrated Electronics, Intel.

By 1961 transistors were the foundation of a fast growing, billion dollar, industry. In 1963 a single transistor cost several dollars to buy. That transistor corresponded to half a storage bit and cost as much as an automobile tire at the time. Today (2012), flash memory costs about $1 per gigabyte (8 billion storage bits!) to buy, enough storage to encode the text of all the books in a small town library and it will be cheaper by the time you read this article. Consider that the transistors in state-of-the-art chips today are so small that 4 million of them will fit into the period at the end of this sentence. The industry is today a $250+ billion-a-year juggernaut. The long lived revolution created by the three fathers continues today with no end in sight.

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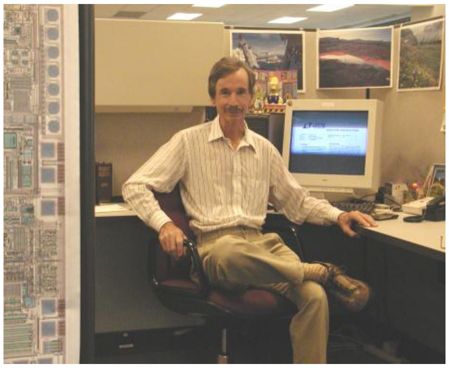
The Author



Dave Laude began a lifelong passion for electronics while in elementary school. By the end of middle school he had competed in four science fairs, taking 1st Place in three and 3rd Place in one. As a teenager he repaired radios and TVs, experimented with circuit designs and constructed his own measurement and audio equipment. These experiences became an appreciable asset to his future formal training. The invention of the transistor a few years before his birth allowed sufficient time for progression to the integrated circuit and for him to make a career of its circuit design. A high school field trip to the local junior college in 1969 exposed him to his first integrated circuit during an electronics career presentation where he acquired his first sample. The unlidded packaged chip with its gold plated leads looked to him like jewelry at the time so he gave it to his girlfriend, not giving any thought to the possibility that he might be designing them some day. Up through earning a Master of Engineering degree in Electrical Engineering in 1977 he had few thoughts of integrated circuit design until an ad appeared on the college bulletin board that changed his life. An interview with Harris Semiconductor yielded two job offers, one for digital and the other for analog IC design. He chose analog and never regretted it.

During his career he designed high precision analog and communication integrated circuits for Harris Semiconductor (now Intersil); GaAs analog, digital and MMICs for Ford Aerospace; analog for Ford Motor Company; and power for Linear Technology Corporation. Throughout his career he was distinguished for his exceptional success rate on the initial design of ICs by having no or only minor problems. He has authored a dozen technical papers and presented at a half dozen electronics conferences including the ISSCC, CICC and GaAs IC Symposium. He also has been awarded five patents. Additional formal studies include anthropology and archaeology and he is a founding member of The Mars Society.

He had the honor to spend a day with Seymour Cray of supercomputer fame and early user of transistors in large scale computers. That day was in the mid 1980s when Dave was designing GaAs gate arrays for Ford Aerospace and Cray was interested in utilizing the technology for his next generation supercomputer. Dave evaluated Cray's proprietary logic circuits and listened to him as he talked with enthusiasm and detailed knowledge about important facets of supercomputer design. Cray told Dave, "I will search the world over to find what I need." By use of the technological revolution in semiconductors and your help, Dave hopes that this historical presentation finds its way "the world over" too.

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