From Germanium to Silicon

A History of Change in the Technology of the Semiconductors

by Philip Seidenberg

Silicon has been the dominant semiconductor material since the middle 1960s. Today, probably 95% of all semiconductors are fabricated in silicon, yet the first transistor was a germanium device. Until 1960 most design engineers preferred germanium to silicon for computer logic circuits, when, suddenly, germanium was out, and silicon was in. What caused this abrupt shift to silicon? An answer to this question requires some understanding of how and why solid-state scientists went about their research.

This chapter explores the technical choices concerning the use of germanium and silicon as semiconductor materials made by scientists and engineers during the period from 1947, the year the transistor was invented, until 1960 when the design shift from germanium to silicon occurred. During this period, the scientists and engineers at Bell Telephone Laboratories (BTL) were the world's leading investigators of the properties of semiconductors. With few exceptions, scientific research on the transistor was dominated by BTL; from 1947 through 1959, twenty-four of the forty-four papers cited as pioneering papers in semiconductor device technology were written by BTL researchers.[1] The remaining twenty originated from fourteen entities, split evenly between the corporate world and the academic/government complex. In fact, it was not until the end of the 1950s that other industrial laboratories begin to challenge the dominance of BTL in semiconductor research and development. This is in stark contrast with the relatively minor role that BTL and its manufacturing arm, Western Electric, played in semiconductor manufacturing and sales. Through 1958 Western Electric produced 1.315 million transistors,[2] representing less than 2% of the total amount of transistors produced by the semiconductor industry during this period.[3]

In spite of its secondary role as a semiconductor supplier, the course of semiconductor research was shaped by the scientific and engineering achievements at BTL during the 1950s. While most of the semiconductor industry concentrated on manufacturing germanium transistors and diodes during this decade, BTL spent most of its research dollars on silicon devices. This research, coupled with the response by the rest of the industry, led to the development of the surface-stabilized silicon transistor and diode, which in turn signaled the replacement of the commercially dominant germanium by silicon as the leading semiconductor material. In this chapter, I will argue that the precipitating cause for silicon replacing germanium, particularly in computer logic, was the use of a silicon dioxide film to stabilize the surface of silicon semiconductors. This was the most important factor in the development of the planar process, which led first to the dominance of the silicon transistor and then to the integrated circuit.

There is very little historical research on the important change from germanium to silicon. Most historians exploring the semiconductor field recognize the significance of the planar process, but treat lightly the progress leading to this innovation. The seminal work on semiconductor electronics refers very briefly to the stabilization of the silicon surface[4] and another established historical work devotes slightly over half a page to the "surface stabilization of silicon by the oxide masking process."[5] An important book on technology transfer in semiconductors chronicles the changeover from germanium to silicon but offers no insight on causes.[6] None of these texts indicates that the replacement of germanium by silicon was an important event in the history of technology, despite the fact that many scholars consider the transistor as the most pervasive invention of the last half of the twentieth century. Furthermore, the works that examine progress made in the physics of semiconductor surfaces do not expound on its influence on technology or industry. The volume on electronics technology and the physical science in BTL's *A History of Engineering and Science in the Bell System* offer a non-technical overview of what happened in surface physics and processing during the 1950s, yet BTL's historians present no explanation or interpretation of what the replacement of germanium by silicon meant to semiconductor manufacturers and their computer customers.[7]

When they do contemplate the demise of the germanium semiconductor, historians often ascribe it to the influence of the Defense Department. It has been argued that aggregate funding figures for transistor development can be used as a gauge for military influence on semiconductor technology, and that military semiconductor technology spilled over into the commercial economy.[8] Although the military did fund silicon transistor development during the 1950s, both military and commercial computer manufacturers almost exclusively used germanium diode logic during this period because germanium diodes could be mass produced more reliably and less expensively than could any other semiconductor. For example, the Minuteman Missile Program, which was probably the most important military program for semiconductor manufacturers in the late 1950s, used germanium diode logic in its guidance system. Consider, also, that digital logic, the preferred choice among circuit designers for commercial computers, required large numbers of inexpensive and reliable switching elements. The germanium gold-bonded diode fit their requirements. The tube and electromechanical relay were large power-hungry devices. The transistor, a three terminal device, suffered from low yields and unreliable performance when compared to the two-terminal diode. Germanium diodes were high-yield economical electronic switches manufactured in volume by reputable and reliable vendors. Clearly, the question of which material, germanium or silicon, would dominate semiconductors was not driven by military considerations.

Much of the literature about the military's early influence on the semiconductor field was written during the 1980s, during the Reagan years of military spending. As Alex Roland has observed, "A kind of presentism moves and infects much of this (1980s) literature." Aggregate research funding by the Defense Department favored silicon devices, but it was germanium that the military purchased for high-volume logic requirements. Even at BTL, a virtual hotbed of silicon research, practically all semiconductors manufactured through 1958 used germanium as the basic or starting material.

Semiconductor development has been driven primarily by the study of the physics and chemistry of the body and surfaces of its starting material. The body—the region of the material away from the surface—is a homogenous periodic structure. Because it poses lesser obstacles to theoretical comprehension than the surface, it has been easier to analyze and measure. For a long time solid-state theorists implicitly assumed that the properties of semiconductors were determined strictly by what happened in the body of the material. The surface—construed here as the boundary area between the body of the semiconductor and any other medium—does not have the symmetry and periodicity of the body. Only a few atomic layers deep, the surface influences profoundly the semiconductor action in the body. These atomic layers of material foreign to the body often are difficult to identify and neutralize.

Early efforts to understand semiconductor action depended largely on empirical inquiry. Theoretical concepts were not formulated until the introduction of quantum mechanics into semiconductors and the explanation for the behavior of electrons in metals and semiconductors. AT&T's corporate strategy for basic research at BTL gelled in the period 1925 to 1935 after the introduction of the new quantum physics. The idea of applying basic science to technology became embedded in BTL strategy. As historian Lillian Hoddeson has noted, "by the mid-1930's the problems, approaches and atmospheres of fundamental research at Bell Labs were remarkably similar to those in university laboratories."[9] Mervin Kelly set the research and development (R&D) parameters for BTL after World War II. Kelly, the vice-president of BTL, decided to focus R&D activities on semiconductors in order to develop a solid-state amplifier for telephone applications. Before the war, Kelly had been interested in substituting electronic relays for mechanical relays in telephone exchanges."[10] The Second World War changed BTL's focus from peacetime research to wartime engineering.

The war accelerated semiconductor development as scientists were transformed into engineers to work on germanium and silicon crystal rectifiers for radar and radio equipment. Scientists and engineers selected germanium and silicon for military research because they were elemental semiconductors with an orderly atomic structure. Germanium and silicon crystallize in a diamond lattice, consisting entirely of one type of atom. They possess a less complex structure than selenium or certain intermetallic compounds such as copper oxide, which were used extensively in rectifiers from the 1920s. Scientists at BTL anticipated easier chemical processing and fewer structural defects in materials that showed the least crystal complexity.

After World War II, BTL continued its pre-war research strategy. In the post-war social context, technology meant progress. Radar had saved Britain from the Luftwaffe in 1940. The atomic bomb had crushed Japan in 1945. Technology could win the peace as it had won the war, with the United States lighting the way for the world. Frederick E. Terman, the Stanford University professor who headed top-secret radar research at Harvard University during the war, summed up the feeling of the scientific community when he said World War II showed "science and technology are more important to national defense than masses of men" and "how essential the electron was to our type of civilization."[11] It is in this environment that BTL embarked upon a sustained research-and-development effort which drove progress in the semiconductor industry during the 1950s.

Solid-state physicists interested in doing research in basic science in the post-war period were faced with only one real choice if they preferred to work in industry rather than academia; BTL was the premier industrial laboratory for solid-state research. The management at BTL was intent on attracting talented researchers and creating an atmosphere of fellowship[12] and the result was a research facility which could be compared favorably with those of the leading universities in the United States.[13] George F. Dacey, who worked for William Shockley, recalls that Kelly was insistent on recruiting only the best people that could be found. Shockley, who had joined BTL in 1936, already had achieved a reputation in the field and served as a beacon to attract additional bright solid-state scientists.[14] Morgan Sparks, who took over Shockley's group in the mid-1950s, was impressed with Shockley's great insight as a theoretical physicist. Shockley was not too concerned with the mathematics of a problem as long as he understood most of the figures. Shockley also evinced a great interest in device applications[15] and appeared to approach a problem with a right mix of the theoretical with the practical. Dacey and Sparks recall the frequent meetings, both formal and informal, held at BTL to discuss the almost daily appearance of new semiconductor phenomena ensuing from solid-state research. Progress was so rapid in semiconductors that it dominated the meeting schedules. By 1950, Shockley had about twenty people in his solid-state physics group, which ultimately grew to nearly one hundred by 1960 under the directorship of Dacey, one of Shockley's successors.

Typical of the people drawn to BTL after 1950 was C.G.B. Garrett. Garrett, who was a graduate of Cambridge University, and an instructor in physics at Harvard University, joined BTL in 1952 to do research on semiconductor surfaces because he felt that it could result in professional recognition. Moreover, BTL could afford to pay well and the laboratory atmosphere was collegial. Technology diffused easily and rapidly among all research and development groups. Regularly scheduled, topical and ad hoc meetings characterized the diffusion of semiconductor knowledge within BTL. It is in this ambiance that semiconductor research flourished.[16]

A tabular view of the major milestones in transistor research and development between 1947-1959 reveals the impact of BTL's research in this area (see Appendix 1). Of the ten major events instrumental in the demise of germanium as the preeminent starting material, seven originated at BTL while the other three were derived from BTL research activities. Of course, there was considerably more happening in semiconductor research and development at BTL during this time besides these important events. For example, BTL researchers developed the phototransistor (J.N. Shive, 1950), the junction field-effect transistor (G.C. Dacey and I.M. Ross, 1952), the thermocompression wire bonder (O.L. Anderson, H. Christensen and P. Andreatch, 1956), and other significant process and product innovations not directly connected to the history of the replacement of germanium by silicon.

One should not conclude these milestones in technological innovation were part of a continuous stream of

BTL's successes, unaccompanied by individual failures and frustrations. However, the rate of technological progress at BTL during this period did allow the semiconductor industry to grow to about one half billion dollars by 1960.[17] Compare this to the inability of solid-state scientists and engineers to agree on common concepts for a basis of research in the fifteen years from 1931, when the theory of the electronic semiconductor based upon quantum mechanics was advanced. In a review of semiconductor research in a 1955 issue of the *Proceedings of the Institute of Radio Engineers,* G.L. Pearson and Walter Brattain noted that "it took about fifteen years for the full light to dawn" and that there were "many blind spots in the working concepts about semiconductors in the nineteen thirties."[18]

The quality and quantity of the researchers at BTL, operating in an atmosphere of easy communication and unfettered disclosure, contributed considerably to the semiconductor industry's high rate of growth during the 1950s. The strategy of the management to encourage the researchers to be independent promoted basic solid-state research. Brattain remembers that after many years of research trying "to understand what was really going on in the simplest of semiconductors, silicon and germanium," he began "to lose faith." However, he felt "no pressure from management to continue or to change fields."

What had influenced Shockley and his two colleagues, Brattain and Bardeen, to join BTL and concentrate on the study of semiconductor surfaces? In 1972, in an issue of the *Bell Laboratories Record* celebrating the 25th anniversary of the transistor, the three scientists recalled the personal interests that led to the discovery of the transistor. The leader of the group, William

Shockley, who obtained his doctorate by studying the behavior of electrons in crystals, was attracted to BTL in 1936 by the opportunity to work with C.J. Davisson, an eminent physicist in the field of electron behavior.[19] Walter Brattain, the oldest of the three, evinced an early interest in quantum mechanics and entered the field of surface physics at BTL in 1929 after receiving his doctorate. In 1937 Brattain met Davisson when the latter used Brattain's laboratory to demonstrate his work on electron behavior. John Bardeen, who joined BTL in 1945, had no experience with semiconductors, but prior to the war he had been interested in the theory of metals. He was anxious to "return to solid-state physics after five years at the Naval Ordnance Laboratory in Washington, D.C."[20] Trained originally as an electrical engineer, he had returned to school at Princeton after several years in industry to obtain his doctorate in mathematical physics, drawn there by the opportunity to study quantum theory under Einstein.

All three scientists attributed the success of their research to the supportive atmosphere created by the BTL in which management allowed those in research to spend many years, much money, and the talents of many people to explore solid-state physics. From their recollections, it appears that all three were motivated by an interest in surface physics and electron behavior, and an opportunity to study and work with eminent scientists in their chosen fields. The physical reality of the microscopic world of atoms opened new vistas for students of physics, particularly those exploring electron behavior in solids. On the 25th anniversary of the transistor, John Bardeen recalled that he and Walter Brattain discovered the transistor as a result of follow-up experiments on some consequences of Bardeen's published investigations of semiconductor surface properties.[21] Shockley, who with Bardeen and Brattain received the Nobel prize in 1956 for the invention of the transistor, had theorized in 1939 that localized states can exist at the surface of a semiconductor.[22] However, solid-state physicists did not realize the importance of these surface states at the time. The accepted theories of semiconductor action formulated prior to World War II assumed that rectification was closely related to the polarity and magnitude of the contact potential at the interface between a conductor (metal) and a semiconductor, or between two different semiconductors. The polarity and magnitude of the contact potential depended upon the difference in work functions of the metal and the semiconductor. However, experimental measurements did not confirm the predictions of the theory. There was little correlation between the work function of the metal and the contact potential.

This perplexing phenomenon was made wholly intelligible by Bardeen's hypothesis in 1947. Surface properties rather than the contact potential at the interface of the metal and the semiconductor were the governing factors for device rectification. Bardeen theorized that electrons from the body of the semiconductor material become trapped and immobilized at the surface, repelling other electrons in the conduction band. This produced a layer of depleted conductivity below the surface.[23] He further theorized that surface states occur when the body of the semiconductor material is abruptly terminated, allowing electrons and holes (the absence of electrons) in the forbidden energy gap between the valence band and the higher-energy conduction band. Normally, in the body of the semiconductor material, electrons exist in the conduction band and holes in the valence band. Between these two bands is the forbidden gap where neither electrons nor holes reside unless trapped by impurities (surface states tend to act like impurities in permitting electrons and holes to have energies in the forbidden gap). Trillions of surface states exist on a square centimeter of semiconductor material, dominating the electrical properties of the structure. These surface states work against any electric fields or currents applied in accordance with circuit design and also work to neutralize any desired imbalance in electrons and holes by tending to return the semiconductor to its condition before the application of the electric field or currents. Realizing that these surface effects can dominate the body properties of the semiconductor, Bardeen and Brattain conducted experiments to change the surface potential of germanium. It was during this research that they invented the transistor[24] (Appendix 2a). Thus, the mutual interest of these two physicists in electron behavior in solid states led them to this important discovery.

The invention of the transistor sparked an heightened interest in semiconductors. Prior to the transistor, semiconductors played a minor role in electronics research, except in detector applications for radar systems during World War II. The discovery of the transistor spurred scientists and engineers to enter the exciting world of microscopic behavior. As the news of the discovery spread to the electronics industry, designers and their managers, particularly those in the military and in the emerging computer industry, wanted more information on how these devices worked. The military had a continual need to reduce power consumption and size in its weapon systems and the incipient computer industry needed an small economical high-speed switch to implement digital designs.

Interest in semiconductors mounted during the early 1950s when Shockley developed in 1949 the theory of *p-n* junctions in semiconductors and the *p-n* junction transistor.[25] The junction transistor was more stable than the point-contact transistor; structurally, the latter was more fragile. The structure of the junction transistor was less complicated and better understood than that of the point-contact transistor and by 1956 the junction transistor had passed the point-contact transistor as the most commonly used transistor type in the Bell System.[26]

Shockley, Morgan Sparks and Gordon K. Teal experimentally confirmed Shockley's theory in 1950 when they produced a number of germanium junction transistors for circuit analysis.[27] Shockley's junction transistor went on to become the single most important solid-state device structure in the 1950s. The three scientists formed the junction during the process of growing single crystals of germanium. In a crystal pulling furnace, a small single crystal of *n*-type (excess of electrons) germanium is lowered into already molten polycrystalline germanium. The seed barely enters the top of the melted germanium whose temperature has been raised to a value slightly above the melting point of germanium. When the *n*-type crystal has grown to the appropriate length to form the collector region of the transistor, a pellet of *p*-type (excess of holes) material is introduced into the melt. This quickly converts the growing single crystal to a *p*-type in order to form the base region. Then, a second pellet of *n*-type material is added to form the emitter region. The result is an *n-p-n* structure whose *p*-type base region is about 0.5 millimeters wide.

The single crystal is then cut into small bars so that each bar is an *n-p-n* structure (see Appendix 2b and 2c).[28]

Most of the transistor research performed in the 1950s focused on the junction transistor. A crucial development was General Electric Corporation's success with the alloy junction process, an inexpensive technique for manufacturing junction transistors and diodes by fusing under elevated temperatures a pellet containing *p*-type impurities to *n*-type germanium. When the crystal cools, a *p*-type region forms in the region under the pellet, resulting in a *p-n* junction.[29] The alloy junction process was an inexpensive and simple method for producing germanium transistors and diodes and was used by most high-volume semiconductor manufacturers in the 1950s.

Shockley's theory led to a better understanding of what occurs at the interfaces of metals and semiconductors. It demonstrated that *p-n* junctions can replace the wire contacts of a point-contact transistor to obtain transistor action. In addition, Shockley's work on the *p-n* junction affected the manufacturing process for the point-contact transistor. D.K. Wilson, a BTL development engineer, observed that a pulse or series of pulses in the forward direction improved dramatically the electrical properties of *n*-type germanium point-contact transistors and diodes. It appeared that these electrical pulses heated the immediate area under the metal contact to form a *p*-type region resulting in a *p-n* junction.[30]

The advances made in understanding surface characteristics generated renewed interest in the body of the semiconductor material. Scientists had long understood that uncontrolled impurities in materials tended to mask the latter's true properties; revealing the intrinsic nature of a material depended upon removing its impurities. The purification of germanium and silicon was based upon an ancient method of purifying a crystalline solid through repeated fractional crystallization until 1951, when a BTL metallurgist discovered a new approach. Using a zone-melting technique, W.G. Pfann was able to purify germanium to a level unattainable in silicon or any other semiconductor material,[31] but zone-melting was not as effective in purifying silicon because it melted at a higher temperature than germanium. In addition, the containers used in the purification process held impurities which easily contaminated silicon, a more chemically active material than germanium.

Besides purity, it was found that germanium and silicon offered better semiconductor action when their normal polycrystalline structures were grown into a single crystal. Impurities tend to diffuse more rapidly along the boundaries that separate crystals of different orientation in a polycrystalline aggregate than through the individual crystals themselves. When the transistor was invented, two laboratory methods for growing single crystals were available. With the introduction of high-purity polycrystalline germanium, BTL researchers adapted these single-crystal growing techniques for germanium. At the same time that Pfann was developing the zone-melting process for purification, G.K. Teal and J.B. Little, after growing their first single crystal in 1948, routinely grew single-crystal germanium.[32] The feat of these two BTL solid-state chemists demonstrated the importance of single-crystal germanium in the manufacture of reliable transistors in high volume. A high-purity single crystal has an intrinsic electrical conductivity, affected only by variations in temperature. This electrical conductivity can be manipulated by the controlled introduction of impurities. The impurities, rather than temperature, then control the resistivity of the material until a certain temperature level is reached, at which point, the temperature becomes the predominant factor. Operation of the semiconductor beyond this temperature level results in device failure.

One would expect that by 1954, the transistor, which had been in production since 1951, would lead in the sales of semiconductor devices. The junction transistor was proving itself as the solid-state amplifier which BTL had sought as a replacement for the less reliable, power-consuming vacuum tube. Additionally, the point-contact transistor, the structure in which the first transistor was developed, was being used in many non-amplifier applications such as oscillators, where the amplitude of the signal was considerably more than the generated electrical noise. Why, then, did the unit sales of diodes and rectifiers consistently lead transistors annually during the 1950s? In 1955, the unit sales of germanium and silicon diodes and rectifiers were 23.5 million versus 3.6 million for transistors; in 1959 the figures were 120.1 million and 82.3 million respectively.[33]

The reason is that engineers began to understand more readily the properties of germanium. Manufacturing engineers raised yields resulting in an increase in performance and reliability and a decrease in cost. Two-terminal devices (diodes and rectifiers) proved easier to manufacture reliably for high-volume applications than three-terminal transistors, in spite of the fact that three-terminal devices effectively isolated inputs and outputs. The result was that military and commercial computer manufacturers—

he latter being the largest user—preferred germanium diodes for switching applications. The germanium diode led factory unit sales of semiconductors in the 1950s. In 1954, the year that Texas Instruments announced the first transistor fabricated in silicon, 1.3 million germanium transistors were produced and factory sales of germanium diodes and rectifiers totaled 16.5 million units.[34] Although the invention of the silicon transistor in 1954 offered circuit designers an opportunity to use silicon, the technology of germanium devices, particularly diodes, was so well established that silicon could not match the reliability and yields of the germanium devices in large-scale production. Silicon was chosen mainly by the military establishment when a rugged application required high-temperature operation (125° C). The normal operating temperature of germanium devices did not exceed 70° C.

Computer designers preferred the germanium junction diode as well for their logic circuits because of its high-speed switching capability. Diodes designed for switching allow practically no current to pass until a threshold voltage is reached. At that point, a large current is allowed to pass, energizing the circuit. Diode resistance drops sharply and becomes relatively independent of the voltage across the device. The diode functions as an electronic switch, faster and longer lasting than any mechanical or electromechanical switch. Germanium switching diodes also exhibited a lower threshold voltage than silicon devices when turned on, a useful property for logic designers trying to minimize voltage drops.

The circuit designer in the 1950s could select from several types of logic circuits. In systems where a large number of circuits were employed, diode logic was chosen because the germanium diode was relatively inexpensive, reliable and small. It was a fast electronic switch and operated at low power levels. For amplification, a function that diodes could not perform, engineers employed small numbers of transistors or vacuum tubes.

It was not uncommon to find large numbers of germanium diodes in a single computer system. A typical system might contain close to 400,000 components including not only diodes and transistors, but also capacitors, resistors and coils. Germanium diodes dominated the system, comprising about 40% of the component population, outnumbering even resistors, the most commonly used component in other electronic equipment.[35] The transistors were used as inverting amplifiers to compensate for circuit losses. Engineers preferred silicon diodes where pure rectification was the goal, typically in power supplies where higher voltages and temperatures dominated. Circuit designers selected transistor logic primarily for control applications where speed was not essential. Resistor-transistor logic (RTL), although relatively slow, is easier to design because it contains only one active device. A typical RTL circuit contained three resistors which performed the logic operation, and a transistor which provided an output voltage level opposite to the input level. On the other hand, diode logic could contain up to five diodes. The number of transistors used in control systems in no way matched the huge amounts of germanium diodes employed in data processing systems.

By 1959 germanium dominated electronic circuits and the worldwide electronics industry was consuming more germanium diodes than any other type semiconductor.

Design engineers selected the germanium diode for most switching circuits in military and commercial computer systems where high-temperature operation was not absolutely essential. The annual factory sales of germanium diodes and rectifiers in 1959 had reached over 100 million units compared to 4.8 million silicon transistors. In 1959 the average selling price of a silicon transistor was $14.53, compared to $1.96 for a germanium transistor. The average price for a silicon two-terminal device, diode and rectifier, was about four times that of a germanium unit, $1.89 versus $0.48.[36] Why, then, did logic designers abruptly terminate new designs in germanium in 1960? The answer lies at the surface of the transistor.

By the mid-1930s, most semiconductor researchers had accepted the premise that rectification was not a property of the body of the semiconductor material, but a surface effect. When it became clear that rectification occurred at the surface, researchers urgently sought a scientific explanation.[37] One began to emerge in the wake of the intense efforts in applied science that were occasioned by World War II.

Because germanium and silicon were elemental materials and relatively simple to understand in terms of quantum mechanics, most of the semiconductor research was concentrated on these two materials. After the war, researchers at BTL preferred to work with germanium because it proved to be a more tractable material than silicon. Germanium could be manipulated at lower temperatures and was not easily contaminated. However, as device structures diminished in size, it became apparent to the research staff at BTL that silicon was the material of the future.[38] Its intrinsically higher energy gap meant that silicon devices could operate at a significantly higher ambient temperature than could germanium. At a given temperature, the rate of thermally generated charge carriers are lower in silicon than in germanium because the former requires more energy to move an electron from the valence band to the conduction band, resulting in lower leakage currents. In addition, silicon has a higher thermal conductivity, allowing heat to flow away from the junction at a much faster rate in silicon than in germanium.

Thus, by the early 1950s, Jack A. Morton, who headed up transistor development at BTL, and who worked very closely with the BTL research staff and those who ran the transistor manufacturing operations at Western Electric, began shifting development activities to silicon. However, it was not easy to transfer scientific advances in silicon made at BTL to the production lines at Allentown, PA. Silicon proved to be more chemically active and more easily contaminated than germanium, causing low yields in each step of the manufacturing process. Additionally, the high melting point of silicon, higher than that of germanium, created difficulties in controlling the process. When William Pietenpol, a Morton successor, left BTL in 1958, the Allentown facility was not producing any silicon transistors. Even though silicon was being used for rectifiers and diodes, the only transistors manufactured at Allentown were made of germanium.[39] AT&T exercised a tight control over semiconductor manufacturing operations which precluded any precipitous move into silicon transistors unless the manufacturing management had a firm control of the process.

During the same period, the rapid progress made in semiconductor research at BTL prompted the elevation of this activity to a departmental footing equal with physics, chemistry and metallurgy. However, because of the continuing advances made in all areas, these departmental lines were not neatly recognized in practice. There was a considerable blurring of departmental lines as researchers exchanged information both formally and informally on a constant basis; Morgan Sparks remembers that friendship and similarity of research interests tended to override departmental formalities.[40]

The progress made in understanding body phenomena in transistors and the availability of high-purity, single-crystal material contributed to an overall effort to explain surface effects. In 1954, C.A. Lee of BTL developed a process for diffusing the impurities of one conductivity type into the surface layers of a semiconductor body of opposite conductivity (i.e., *n*-type impurities into a *p*-type body, or *p*-type impurities into an *n*-type body) at elevated temperatures under very controlled conditions. The immediate advantage of this process was to increase greatly the frequency range of the transistor.[41] It was easier to accomplish this diffusion in germanium than in silicon transistors; silicon was not available in the purity that could be had with germanium and the diffusion process in silicon required higher temperatures. Although BTL scientists in 1955 did demonstrate diffusion in silicon, the yield of these devices was poor and their reliability was questionable.[42]

In the same year, L. Derick and C.J. Frosch devised an oxide-masking technique for controlling against undesired impurities during the diffusion process by thermally forming a silicon dioxide mask on a wafer of silicon. This was accomplished by "heating the wafer to between 1100° C and 1400° C in an oxidizing atmosphere to form a surface oxide film . . . between 1500 and 3500 Angstroms thick."[43] The mask is removed from selected portions of the wafer and the desired conductivity-type impurities are diffused into the silicon body, where the oxide film had been removed. The oxide film is then re-grown in water vapor and the vapor of an impurity opposite in conductivity to the first impurity. The second impurity can be diffused through the silicon dioxide layer to form a diffused transistor junction. For instance, into a *p*-type material, phosphorus, an *n*-type impurity, is diffused through the windows in the oxide mask. The silicon dioxide film is reformed and boron, a *p*-type impurity, is introduced to form a *p-n-p* diffused junction transistor. Diffusion, a controlled high-temperature process at the atomic level, permitted a more precise concentration of desired impurities.

This technique of using an oxide mask to shut out undesired impurities was recognized at BTL as an important step in transistor manufacture.[44] However, it did not directly address the problem of surface effects and it remained for another BTL research team to demonstrate successfully the stabilization of a silicon surface. In 1957 M.M. Atalla and his group at BTL stabilized a silicon surface by thermally growing on it a silicon dioxide film. They had been systematically investigating the silicon/silicon dioxide interface and determined that slow states at the silicon surface were eliminated by the oxide film. The group cautioned that "the oxidation process not only provides a stable surface but a completely new kind of surface with its own characteristic properties."[45] Atalla and his group had used silicon dioxide, chemically identical to quartz, to passivate the silicon surface. A very thin film of silicon dioxide does grow naturally on a clean surface of silicon, protecting the surface from corrosion much like that of a naturally occurring copper oxide on copper but the natural silicon dioxide film is too thin to give chemical protection or to act as an insulator. However, by thermally growing a thicker film, Atalla and his group not only protected the surface from external contamination, but also effectively reduced the density of surface states at the silicon/silicon dioxide interface by several orders of magnitude.

Meanwhile, no progress was being made on the surface stabilization of germanium and BTL had shifted its emphasis to silicon by the mid-1950s. None of the members of the former BTL staff interviewed for this chapter remembered any specific work being performed to form an oxide of germanium. Outside of BTL, the major germanium producers were not committed to use money or personnel for serious applied research on surface effects in germanium. Nick Calandrello, a development engineer with Clevite Transistor Products, a major germanium device manufacturer in the 1950s, recalls no program to grow oxide films on germanium. John Royan, a research engineer at Transitron, a leading germanium diode producer, worked unsuccessfully in the late 1950s to produce a stable germanium oxide. In 1960, he was hired by National Transistor Corporation, a newly formed firm that had concerns, later found to be baseless, that Transitron was achieving some success with germanium oxide films.[46] James Battey, a physicist with Sylvania Electric, a leading tube manufacturer making germanium devices, recalls no program for the oxide passivation of germanium.[47] Germanium device manufacturers were aware of the benefits of thermally grown oxide films but were preparing to meet the threat by manufacturing silicon devices because they were unable to develop a stable oxide film for germanium.

In 1959, Jean Hoerni of Fairchild Semiconductor Corporation implemented in production the oxide-passivation techniques of Atalla's group. An *n-p-n* planar-passivated silicon transistor was fabricated using key processing techniques first discovered at BTL. The oxide mask for diffusion was based upon the work of Derick and Frosch, although the data on mask thickness, diffusion times and temperature were derived from the first modeling of the oxide mask by C.-T. Sah and his colleagues at Fairchild.[48] Hoerni's device left "permanently in place the coating covering all parts of the *p-n* junction that extend to the semiconductor surface."[49] Electrical contacts were evaporated onto openings incorporated into the mask design for the purpose of attaching leads to the inside of the transistor package. What Hoerni had accomplished was to use BTL's process advances to produce a silicon transistor that lent itself to batch processing, and whose yield, cost, and reliability potential seemed superior to the contemporary methods of germanium transistor manufacture. The key to this device was the oxide-passivation technique developed by Atalla and his group. Sah, a former employee of Shockley Semiconductor Laboratories, whose major contribution lay in oxide masking, agrees that the successful attempt by the BTL group to stabilize the surface of silicon was the most significant technological advance in the development of the silicon planar passivated transistor.[50]

All of the key processes—impurity diffusion, oxide masking, and surface passivation—were developed at BTL. Even the planar structure was not a new concept, although this was the first time it had been used successfully in transistor production. The planar diode, a junction device whose electrodes lie in the same plane, already had been described by a BTL researcher in 1954.[51] The planar transistor is a flat-surfaced structure in which all electrically active regions of the device, emitter, base and collector, terminate in the same plane. This structural planarity was advantageous for oxide masking and oxide passivation (Appendix 2d). Hoerni's feat was to put all these elements together to produce a transistor whose merits were eminently saleable to logic designers looking to incorporate switching and amplification functions into one device.

Fairchild Semiconductor proved to be the right messenger for the new product. The company was founded in 1957 by eight engineers from Shockley Semiconductor Laboratories in Palo Alto, California. Shockley had left BTL in 1954 to capitalize on his achievements. He returned to his hometown to form a semiconductor research company in 1956 where he found little difficulty in attracting young and talented engineers. However, these engineers soon became unhappy with Shockley's managerial style. One quirk which particularly gained prominence was Shockley's penchant for publishing the salaries of his employees on the company bulletin board. They decided to leave the company *en masse* and form their own company

The group obtaining financial backing in 1957 from Fairchild Camera and Instrument Corporation. Logic designers were anxious to sample the planar-passivated transistor. Fairchild Semiconductor was able to provide devices which passed the customers' qualifying tests. By the end of 1960, practically all computer logic designers had switched from germanium diodes to silicon transistors and diodes. The development of the planar process provided the semiconductor industry with the capability of mass-producing reliable miniaturized high-performance silicon devices whose switching speeds, rectification efficiencies, breakdown voltages, and power-dissipation ratings were superior to those of germanium.

The shift from germanium to silicon signaled a dramatic reduction in the price of silicon transistors. In 1960 the average selling price of a germanium transistor was $1.70, compared to $11.27 for a silicon transistor. Five years later, the average unit price of a germanium transistor had dropped to $0.50, but the silicon transistor had decreased more precipitately to $0.76. During the same period, the unit sales of germanium transistors had risen from 119 million to 334 million. In contrast, the unit sales of silicon transistors during the same time had leaped from 9 million to 273 million.[52]

The silicon transistor was one of the few innovative devices not introduced by BTL during the 1950s. However, as Pietenpol has pointed out, the policy of BTL to disclose publicly its progress in transistor research and technology enabled companies such as Texas Instruments, Inc., inventor of the silicon transistor, and Fairchild to develop semiconductor expertise. In the early 1950s, BTL held several disclosure symposia, granting patent licenses under non-exclusive and cross-licensing conditions at very reasonable costs to all comers. Many small semiconductor device companies started manufacturing transistors without obtaining patent licenses, but BTL generally ignored these transgressions. William Pietenpol attributes this open policy to Jack Morton. Sometime after the public announcement of the transistor in 1948, Mervin Kelly instructed Morton to find an answer to "what should be done with the invention of the transistor."[53] When Kelly returned, after a month in Europe, Morton advised him that the best policy would be to disseminate information about the transistor in as broad a manner as practicable, both nationally and internationally. Holding that BTL's primary focus should remain on telephone technology, Morton recommended that the best way to advance BTL's interests would be to publish widely and cross-license all interested parties, including competitors. In this way, BTL could be certain that all advances in transistor technology made by outsiders would flow rapidly into the Bell System. Of course, there are other reasons which could be attributed to this policy of open disclosure. Many of the papers published in the *Bell System Technical Journal* indicate support by the Defense Department under specific contracts. The Defense Department encouraged dissemination in order to rapidly establish an industrial base for the transistor. AT&T also was concerned with anti-monopoly accusations. However, Pietenpol, who later became the director of development for solid-state devices at BTL, believes that it was Morton's vision of how AT&T could best benefit from the invention of the transistor that influenced top management to set the policy for disclosure.

Although the full disclosure policy of BTL helped shape the rapid growth of the semiconductor industry in the 1950s, five years elapsed after the development of the silicon passivated planar transistor before silicon surpassed germanium as the dominant starting semiconductor material in production. The reason lies primarily in the dynamics of the business practices of the semiconductor industry's largest customer, the computer industry. Between 1957 and 1959, computer manufacturers expanded the production of the first generation of electronic computers. In order to recover their costs and accrue a profit sufficient to design the next generation of computers, many managers in the computer industry estimated that five years of system production were required in order to obtain an acceptable return on investment. Kenneth Flamm has suggested that two or three years were needed for a return on research-and-development investment plus another two or three years "for significant technological rents."[54] This analysis is supported by actual sales of germanium diodes between 1959 and 1965. In 1959, unit sales of germanium two-terminal devices were 66.5 million, while in 1965 they had increased six-fold to 383.1 million; most of these devices were germanium gold-bonded switching diodes.[55]

Not only did computer manufacturers need time to recoup their investment, but silicon device vendors needed at least two of these years to negotiate specifications, estimate costs and pricing, submit lots for qualification testing, and renegotiate specifications and prices. Submission for military qualification generally took more than a year longer. During this time production sites were selected, facilities built, and factories manned. Manufacturers of germanium logic devices encouraged the delay in switching over to silicon by dropping prices as cost reductions were realized from their high-volume manufacturing experience. These suppliers continued to increase yields and refine manufacturing processes to a level where the average selling price of a germanium logic diode fell below ten cents, about one-quarter to one half-lower than that of a silicon diode, and at least five time less expensive than a silicon switching transistor.[56]

Some questions still remain: Was it inevitable that silicon would replace germanium? Was silicon an inherently superior material? The history of the virtual replacement of germanium by silicon underlines the significance of both material properties and technical processes in the new specialization of solid-state electronics. The research and development efforts of professionals who select their fields of investigation based upon technical interests played a large role in overturning germanium in favor of silicon, in particular the BTL researchers who chose to study the surface effects of silicon rather than germanium. Efforts by other corporate research and development groups to passivate the surface of germanium appear not to have been sustained by the same quality and quantity of scientists working on silicon at BTL. No one to date has grown a stable oxide passivation layer on germanium, in spite of the fact that in the 1950s many companies were totally dependent upon germanium devices for their sales and profits. It was not inevitable that silicon would replace germanium. Silicon was developed by BTL researchers because they perceived that its material properties were more useful for telecommunications than those of germanium.

Morgan Sparks recalls that the reason silicon was chosen for investigation over germanium was because the forbidden energy gap of germanium is smaller than that of silicon. The smaller germanium gap between its conduction-band minima and valence-band maxima meant that the leakage currents of germanium would be higher than those of silicon, permitting the latter to operate safely at significantly higher temperatures than the former.

Why did the BTL scientists not select a parameter of germanium which was inherently more useful to that of silicon as guidepost for research? Electron and hole mobilities in germanium are considerably higher than in silicon, making the former a much faster switching material, but none of the BTL researchers interviewed mentioned switching speed as a factor in favor of continuing research on germanium; most mentioned the superior operating temperature of silicon, the implication being that within reasonable application limits, reliability was preferable to performance. Another issue, unexplored here, is that switching speed is presumably a parameter more useful in computer logic than in telephone amplification.

Eventually, the inherent performance advantages of germanium in switching circuits were overcome by the intensive investigations of silicon by BTL and the rest of the industry. Silicon had surpassed germanium in switching speeds by the beginning of the 1960s. Developers shortened transit times by reducing the feature dimensions of the transistor. Germanium, as its dimensions were reduced, became more difficult to handle because the material had a poorer thermal conductivity than silicon; heat flowed away from the germanium *p-n* junction at one third the rate of silicon.

Silicon replaced germanium through the combined effect of a variety of researchers, properties, and processes all existing in an environment that was dominated by BTL. What happened there supports the belief that "science, although part of a larger social and economic context, is ultimately driven by individual desire and determination."[57] The scientists and engineers at BTL wanted to participate on the leading edge of the new science of the solid state, and quantum mechanics led scientists to investigate the microscopic and unseen, where the behavior of the electron in solids was a mystery to be unraveled and anyone who succeeded in doing so could gain professional recognition. Furthermore, researchers and engineers themselves chose the materials to be investigated. Their decisions were based upon the perception that the properties of elemental semiconductors would be easier to understand and manipulate than the pre-war compound materials. Because the research and development of semiconductors is an interdisciplinary endeavor, progress was needed simultaneously in several areas.

This chapter has touched on other elements of the BTL environment. The overarching objective at BTL was to replace a mechanical telephone system with an electronic one. At a time when science and technology seemed to be the answer for how humans could improve their lot in the world, BTL started its semiconductor research activities long before its competitors and was able to gather a group of scientists who could attract the most talented newcomers to its staff after World War II.

Semiconductor device development can be compared to system development. Although often invisible to the naked eye, the development of a device suffers from the same ebbs and flows more apparent in large systems. In the beginning, the scientists at BTL found germanium easier to handle than silicon. They could purify germanium more easily. The higher processing temperatures required for silicon because of its inherent properties created complexities in handling the material and measuring results. Early transistor structures were large enough to neutralize the limited heat-handling capabilities of germanium. As processing and measuring techniques became more sophisticated, smaller transistor structures could be investigated. Miniaturization to the scientist meant conservation of energy. It coincided with the performance and economic goals of both the military and industry. As BTL scientists and engineers learned to process smaller structures in volume, the properties of silicon contributing to high-density, high-temperature operation pre-empted the performance advantages of germanium. BTL ceased meaningful research on germanium by the mid-1950s and, by 1960, the continuing investigation of silicon had resulted in its acceptance by system designers as the dominant semiconductor starting material. This acceptance happened very quickly because of the recognition by the industry that the oxide passivation of silicon had created a different and apparently superior semiconductor device. However, more than five years passed before design acceptance could be translated into the dominance of silicon in the marketplace. During these five years, BTL's research achievements spurred other major technological innovations including the monolithic integrated circuit and the metal-oxide semiconductor field-effect transistor, both made practicable by oxide passivation.

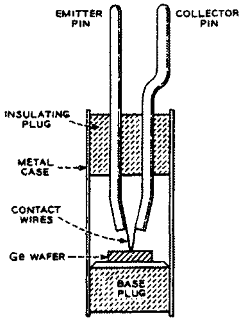
APPENDIX 1

MILESTONES IN TRANSISTOR RESEARCH AND DEVELOPMENT
(1947-1959)

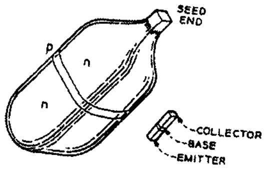
INNOVATION	FIRM	DATE
Transistor	BTL	1947
Single Crystal Germanium	BTL	1948
Grown Junction Transistor	BTL	1950
Zone Refining	BTL	1951
Alloy Junction Transistor	GE	1951
Silicon Junction Transistor	TI	1954
Diffusion Process	BTL	1954
Oxide Masking	BTL	1955
Oxide Passivation	BTL	1957
Planar Process	Fairchild	1959

Compiled by Author

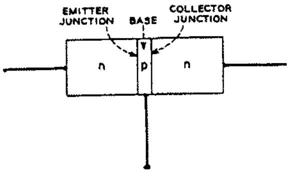
APPENDIX 2



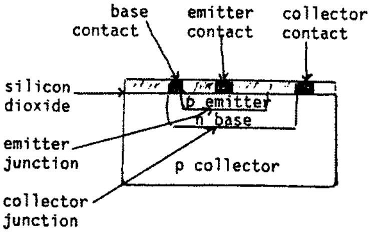
1a. Point Contact Transistor
[Shive: 177]



1b. n-p-n Grown Junction Crystal
[Shive: 188]



1c. n-p-n Junction Transistor
[Shive: 188]



1d. Planar Transistor 1960
(Diagram by Author)

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