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The Materiality of Microelectronics

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This study advocates for 'materials-centered' accounts in the history of technology, and presents such an analysis for the early history of microelectronics. Innovations in semiconductor crystal production were central to the emergence of solid state electronics and the dynamics of the early semiconductor industry. In the late 1940s and early 1950s, the Bell Telephone Laboratories developed novel techniques for growing semiconductor single crystals. These crystal-making techniques were scaled up at Texas Instruments for the production of silicon transistors, and thereby underwrote the firm's rise as a dominant manufacturer of silicon devices. Shockley Semiconductor, a West Coast start-up, sought to gain a competitive advantage in the silicon device business by developing a new technique for producing silicon crystals. The failure of this strategy contributed to the disintegration of the firm, with several key staff members leaving to establish Fairchild Semiconductor. Learning from Shockley's failure, Fairchild Semiconductor developed a low-cost single crystal production capability that allowed it to introduce two milestone microelectronic devices: the double-diffused planar transistor and the integrated circuit.

Keywords: Crystals; Electronic Materials; Innovation; Integrated Circuit; Semiconductor Industry; Transistor; Microelectronics

Introduction

In the early fall of 1986, US concerns about silicon wafers played out in the business pages of the *New York Times*. These wafers—slices of large ultrapure single crystals of silicon—comprised the fundamental starting material for the global semiconductor industry, the manufacturers of the vast array of microelectronic components that were being used to reconfigure computing, telecommunications, industrial production, and military technology, among other prominent sectors. The cause of these concerns was an announcement that a Japanese company was buying one of the only two remaining US merchant producers of silicon wafers. The Siltec Corporation, based in Silicon Valley, had agreed to be acquired by Japan's Mitsubishi Metal Corporation. As the *New*

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York Times reported, some in the US semiconductor industry were extremely worried. One editor of an industry trade journal warned that silicon wafers are the 'most fundamental technology in the electronics industry' and that if the Japanese controlled their manufacture, 'they control everything.'[1]

Just two years later, at the end of 1988, these US worries reached new heights. A leading trade journal, *Electronic News*, evoked the metaphor of Pearl Harbor in announcing that the last US merchant producer of silicon wafers, the Monsanto Electronic Materials Company, had entered into an agreement to be acquired by a West German conglomerate, VEBA AG. While merchant production of silicon wafers would continue inside US borders, every firm would be Japanese or German owned. *Electronic News* likened the situation to a 'modern-day economic attack on America from across two oceans,' and made its case succinctly: 'The United States is totally dependent on foreign producers of silicon wafers for almost all of its electronic products … . This is a potentially disastrous situation because silicon wafers are the basic raw material for most of the US's military and economic technology.'[2]

In the early 2000s, German and Japanese producers of silicon wafers continued to command a dominant global position, with the dire concerns of the 1980s remaining unrealized. However, this episode highlights the importance of a particular material—silicon crystals, and the wafers sliced from them—to the development of microelectronic technology. Indeed, we argue that silicon crystals—alongside efforts to carefully control their chemical composition and to produce them with ever-greater crystalline perfection—were central to the development of microelectronic devices and to the dynamics of the early semiconductor industry.

As such, our account contrasts with most existing historical treatments of microelectronics. Existing accounts are largely 'device design centered' analyses, with the majority of attention devoted to the design efforts of electrical engineers and physicists in their creation of new microelectronic devices.[3] While the events covered by these analyses are certainly vital for our historical understanding of microelectronics, these treatments are incomplete. They give little attention to the materials that made possible new devices and underlaid the development of microelectronic capabilities. Largely missing are accounts of various practitioners' development of practices, capabilities, and knowledge through a deep engagement with semiconductor materials. All but ignored are networks of individuals, organizations, locations, and resources that centered on the production, analysis, and manipulation of semiconductor materials. In other words, standard accounts of microelectronics are 'under materialized.' That is, they underemphasize materials as an analytical category in their study of solid state electronics. For these reasons, a 'materials centered' approach to the history of microelectronics is both a complement and a corrective to the existing 'device design centered' historiographical emphasis.[4]

In the remainder of this study, we address two main questions by laying out a 'materials centered' account of the early period of microelectronic technology. To what extent was crystal making a foundational technology that enabled the creation of new semiconductor devices? Was crystal making, as an internal firm competency, a major determinant of success in the formative years of the semiconductor industry?[5] Our study looks for answers in the examination of five institutional locations in the period from the 1940s through the 1960s. In the late 1940s and early 1950s, the chemist Gordon Teal, in collaboration with colleagues at the Bell Telephone Laboratories, created new machines for producing single crystals of germanium and silicon. Therewith, Teal and his colleagues supplied a wide range of Bell Labs researchers with single crystals of semiconducting materials having unprecedented levels of chemical purity and crystalline perfection. In turn, these advanced materials enabled Bell Labs researchers to achieve an impressive array of laboratory firsts in the development of microelectronic devices. Bell researchers fabricated both germanium and silicon bipolar transistors using a variety of processes for the controlled distribution of impurities into single crystal material.

In 1952, Texas Instruments (TI) hired Teal away from Bell Labs to establish and manage TI's research and development efforts in microelectronics. At TI, Teal transferred and scaled up the crystal making techniques he had championed at Bell Labs for the production of silicon single crystals. This leadership position in advanced silicon crystal production enabled Teal's organization to quickly develop and manufacture the first commercially available silicon transistor, using a grown junction process. As a result, TI attained and maintained a leadership position in the manufacture both of silicon microelectronic devices and of silicon crystals themselves.

Soon after Teal decamped to TI, perhaps the leading light of Bell Labs electronic device design, William Shockley, formed a new firm aimed at the emerging silicon transistor business. Established in Mountain View, California, Shockley Semiconductor Laboratory was a subsidiary of Beckman Instruments, Inc. Seeking competitive advantage in silicon microelectronics, Shockley initiated a large program at his new firm to develop a new technique and machine for producing silicon crystals. The new crystal-growing machine was intended to embody improvements over Teal's technique, yielding purer and more structurally perfect silicon crystals. These efforts failed, however, leading Shockley Semiconductor and its spin-offs, Fairchild Semiconductor and Knapic Electrophysics, to employ Teal's by-then traditional approach. Fairchild Semiconductor's fashioning of robust, practical approaches to the production of silicon crystals allowed the firm to achieve market firsts for two milestone microelectronic devices: the double-diffused planar silicon transistor and the integrated circuit.

Origins: Bell Telephone Laboratories

In the decade and a half preceding the Second World War, the Bell Telephone Laboratories were at the forefront of research and development efforts in electronics. In those years, the emblematic electronic device was the vacuum tube. In the midst of this vacuum tube era, in 1930, a freshly minted chemistry Ph.D. from Brown University joined the Labs. Dallas born and bred, Gordon K. Teal had fallen under the spell of the chemical element germanium during his Providence years. Germanium is a semiconductor. That is, its electrical properties stand somewhere between highly conductive metals and non-conductive insulators. The middle ground that semiconductors occupied became quite important in the late 1930s, when researchers determined that the introduction of particular chemical elements into the semiconducting material could modify and control these electrical properties. Such modification allowed researchers to create novel electronic devices out of the material.

In the late 1920s, Teal spent his graduate studies in a deep engagement with germanium, in efforts to reveal new aspects of its then little studied and little understood behaviors. As Teal put it almost 50 years later, he had formed an emotional attachment to the enigmatic element:

> [Then, germanium] was a material studied only for its scientific interest; its complete uselessness fascinated and challenged me. My concentration on this shiny metallic-appearing material during my graduate school days resulted in a continuing personal sentimental attachment for germanium, which, to me, at least, was and is an exotic element.[6]

At Bell Labs, for much of the 1930s Teal was assigned to the Electro-Optical Department, where he developed new pyrolitic deposition techniques for making key components of television camera tubes.[7] Prompted by radar-oriented developments in the early 1940s, he quickly adapted his techniques to the production of germanium rectifiers. At that time, rectifiers, critical components in radar detectors, were being produced from *silicon* in two forms: 'P-type' and 'N-type.'[8] Chemically pure polycrystalline silicon was infused with particular 'impurities,' elements called 'dopants.' Some impurities reduced the amount of available electrons in the silicon, yielding 'P-type' material. Other dopants provided an excess of electrons, creating 'N-type' silicon. So inspired, in 1942 Teal developed a method for making polycrystalline *germanium* with the controlled addition of specific impurities, yielding the 'P-type' or 'N-type' material at the heart of rectifiers. Quite rapidly, Teal modified his germanium production system so that it created germanium rectifiers *themselves*. In Teal's system, *creating the material was creating the advanced electronic device*.

Teal's germanium rectifier production system allowed the batch production of germanium rectifiers through the controlled mixing of two gases in a reaction chamber—one, a germanium chloride gas, the other a chloride gas of the desired impurity like boron or arsenic. In this reaction chamber, the mixed gas encountered heated filaments that were situated above a series of 'bases,' formed from a metal like tantalum. The mixed gas decomposed as it passed over the heated filaments, depositing layers of a polycrystalline germanium-impurity alloy atop the metal bases. Removed from the reaction vessel, the surface of the germanium alloy was etched, a point contact applied, and a completed germanium rectifier was in hand.[9] Much to his disappointment, Teal's germanium work initially garnered scant interest at the Labs, which was then predominantly focused on silicon for radar rectifiers. Subsequently, while temporarily out of work with pneumonia, Teal saw germanium work restarted at the Labs after outside prompting by MIT's Radiation Laboratory, with the work assigned to his co-workers. Teal spent the rest of the war working on materials for radar attenuators.[10]

The development of the transistor in the immediate post-war period brought Teal back to germanium. In December 1947, Walter Brattain and John Bardeen, members of William Shockley's group, created the first solid state amplifier—the point contact transistor—using germanium. Bell Labs' staff reacted with excitement to the transistor, perhaps none more so than Teal, for the breakthrough was the action of his dear germanium. Within a month, Teal launched a series of internal missives, in which he proposed to spearhead a new program for producing germanium of the highest chemical purity, and in *single crystal* rather than polycrystalline form. Rather than producing the typical, tangled mass of multiple, imperfect crystals in a germanium ingot, Teal wanted to create a single, near perfect crystal of chemically pure germanium. Many at Bell Labs, including Teal, recognized that crystal imperfections, along with chemical impurities, would affect the electrical behavior of semiconductor materials. Teal's argument for single crystals was by analogy with the history of the vacuum tube. In this history, Teal reckoned, technologists had increased their understanding of the fundamental behavior of the vacuum tube by perfecting the *vacuum* within tubes. With a near-perfect vacuum, largely free from the disturbing effects of impurity gases, the basic behavior of the vacuum tube was revealed, and improved devices resulted from the new understanding. Teal argued that the same tactic was required for transistor technology. If germanium were to be produced with the utmost chemical purity, and in single crystal form, then a fundamental understanding of transistor action would become available. Teal believed that such fundamental understanding would lead to new, enhanced devices.[11]

At first, Teal's pleas fell upon near-deaf ears. William Shockley, the head of the semiconductor research group at Bell Labs, could see little advantage in Teal's proposition. Polycrystalline germanium was by then in abundant supply, and Teal's suggested material would be far more expensive and difficult to produce. Shockley, and the like-minded at Bell Labs, figured that, if needed, relatively uniform pieces of germanium could simply be plucked from polycrystalline masses.[12] After several months, in the fall of 1948, Teal finally found his chance to begin his production of single crystals of pure germanium. In an informal discussion with a co-worker, the mechanical engineer John Little, Teal learned of Little's need for a small diameter rod of germanium. Little's assignment was to devise a way to use a small circular saw to chop germanium into slices with minimal loss of material. For Teal, Little's need was his excuse. Teal told Little that he knew how to produce the kind of small diameter germanium rod that Little was after. It was incidental to Little's project that the rod would also be a single crystal of pure germanium.[13]

Working together over the next month, Teal and Little designed and built a new machine, a 'crystal puller,' and with it made their first single crystals of high purity germanium in October 1948. The crystal puller that Teal and Little developed had historical antecedents, particularly in Jan Czochralski's efforts of 1918 and extensions of this technique in the 1920s by physical chemists and physicists like Gomperz, Polanyi, Linder, Hoyem, and Tyndall, among others. In these antecedents, single crystals of metals had been drawn from a molten mass using a 'seed crystal.' These operations took place in the open air of the laboratory. The diameter of the drawn crystal was controlled by pulling the crystal through a disk that floated atop the melt, and the crystal was cooled by jets of air playing upon it.[14] Teal and Little's crystal puller of 1948 was a far more complex device. This complexity was the result of their efforts to maintain the chemical purity of the grown germanium crystal, and to ensure the perfection of its crystalline structure through the careful control of temperatures in different regions of the material.

In Teal and Little's crystal puller, high frequency induction coils melted ultrapure germanium, which was held in a graphite crucible. A seed crystal of germanium, supported on a weighted metal rod, was centered above the melt. This rod, in turn, was connected by a wire to a variable motor. By adjusting the motor, the seed crystal could be immersed into the germanium melt, and withdrawn at a precisely controlled rate. Indeed, a common rate of the pull, 0.19 in/min, was the rate of crystallization of the liquid germanium in the machine—the material's properties governed the pulling rate. As the pulled crystal was withdrawn from the melt, jets of hydrogen gas cooled the crystal at the interface between the solid crystal and the liquid melt. Not only did the hydrogen jets cool the growing crystal, they (along with the temperature of the melt) controlled its diameter. These tactics for temperature control were aimed at maintaining the perfection of the crystal structure, avoiding the imperfections that temperature variations would inevitably entail. Moreover, the use of hydrogen as the cooling gas was deliberate—the gas would not endanger the crystal's chemical purity. In fact, the entire crystal puller was enclosed in a bell jar, through which a steady flow of hydrogen gas yielded a purity-friendly atmosphere.[15]

With his dream of high purity single crystals of germanium realized, and with a working crystal puller in the background, Teal finally secured official approval from Jack Morton, the leader of Bell Labs' transistor development program, to continue the work with Little on single crystals of germanium. So anointed, Teal labored through the first half of 1949 to produce more material, and proliferate it around the Labs. When Teal gave his single crystal material to William Shockley's group, it found fertile soil. Half a year earlier, in the summer of 1948, Shockley had collaborated with J. Richard 'Dick' Haynes, a physicist in his group, on an experiment to settle important outstanding questions about the fundamental physics of transistor action. Explicitly, Shockley and Haynes designed their experimental measurements to be crucial proof that a phenomenon called 'minority carrier injection' was essential to the functioning of the point-contact transistor, and to a new form of transistor that Shockley was contemplating.[16]

Haynes performed the experiment on minority carrier injection using, at Shockley's recommendation, a thin slice of germanium fashioned from a relatively uniform crystal sample that, in turn, had been harvested from a polycrystalline mass. Here, Shockley was following the reasoning that had led him earlier to reject Teal's suggestion of a single crystal growing operation: For a fundamental study of transistor action, a uniform piece of germanium could be selected from the abundant supplies of polycrystalline ingots. In Haynes and Shockley's experiment of 1948, the plucked germanium samples exhibited 'minority carrier lifetimes,' phenomena at the heart of carrier injection and thus to successful transistor operation, on the order of 10 μsec. After Teal supplied his single crystal germanium to the Shockley group in early 1949, Haynes quickly repeated the experiments that he and Shockley had designed, but using Teal's new material. Haynes found that Teal's single crystal material supported minority carrier lifetimes at the 140 μsec level, a *tenfold* improvement over the material sectioned from polycrystalline masses. In a reversal of fortune for Teal, an experiment that Shockley had designed to afford crucial proof of his theory of transistor action had also revealed the superiority of Teal's single crystal material for both device development and fundamental studies. By the middle of the year, everyone on the research side of the house had become converts to Teal's single crystal, none more so than Shockley himself.[17]

This conversion of the semiconductor research effort at Bell Labs to single crystal material coincided with Shockley's publication of a proposed new form of transistor, the junction transistor. Dispelling the need for point contacts, Shockley's junction transistor was formed by three layers of semiconductor material and the two junctions between them. There were two forms, 'NPN' and 'PNP,' meaning a layer of P-type material sandwiched between two N-type regions, or the reverse. In the junction transistor, the sandwiched layer acted like a grid in a vacuum tube, controlling the current that flowed across it from one sandwiching layer to the other. The properties of the junctions between the layers ensured that a small current applied to the middle layer would result in a huge change in the overall flow.[18] Here was a device which resonated strongly with Teal's electronic aesthetic, going back to his work with germanium rectifiers. Perhaps more so than for any other electronic device then envisioned, in the junction transistor the *material was the device*, no more no less.

In 1950, Teal collaborated with another Bell Labs chemist, Morgan Sparks, as well as a highly skilled technician, Ernie Buehler, in pursuit of Shockley's proposed junction transistor. Teal and his co-workers realized that crystal pulling itself was a fast track to the junction transistor, that is, that a junction transistor could be *grown*. In a few months, Teal was able to devise a modification of the original crystal puller that he and Little had created to this end. Teal's modification was an additional mechanical system, with which small pellets of dopants could be dropped into the germanium melt. Teal could then grow a junction transistor in the following way. He began pulling a crystal in the typical fashion, but from an initial N-type melt. After a region of N-type crystal had been grown, he released a P-type dopant into the melt, transforming the germanium melt around the growing crystal into P-type germanium. After a region of P-type crystal had been pulled, he dropped a pellet of N-type dopant into the melt, returning the germanium melt to a N-type state. With a continued pull of additional N-type crystal, a NPN junction transistor had been grown. By 1951, with contributions by Teal, Sparks, and Buehler, and with the assistance of other colleagues, Bell Labs fabricated the first junction transistor.[19]

On the heels of this success, Teal and Buehler turned their attentions to silicon. Not only was silicon better suited for high temperature applications of semiconductor electronics, it also presented new challenges for Teal's crystal growing approach. To melt the silicon, there were high temperatures with which to contend, and the melt itself would be highly reactive, opening its arms to any potential contaminant. Teal and Buehler made a key modification to adapt the crystal puller to silicon: The silicon melt had a quartz crucible, surrounded by a large graphite support block. Having the silicon melt in a silicon-compound crucible would ameliorate the transmission of contaminants from the crucible into the melt. At the May 1952 meeting of the American Physical Society, the pair announced that they had grown silicon single crystals by their modified method, and had, in fact, grown a P–N junction in one of these silicon crystals. They were not far from a silicon junction transistor.[20]

While Teal would leave Bell Labs later that year, the single crystal program he had diffused throughout the Labs set the stage for an astounding array of device developments in the next three years. Using single crystal germanium and silicon, fabricated using Teal's approach and crystal pullers, Bell Labs produced important new forms of junction transistors. There were the first alloy germanium and silicon transistors, where the all-important junctions were formed by alloying metal contacts to doped semiconductor materials. There were the first diffused transistors, in which junctions were formed by diffusing dopant gases into the germanium or silicon substrate. Indeed, in 1955, Morris Tanenbaum, using single crystal silicon grown with Teal's method, produced the first double-diffused silicon junction transistor—a device that would stand at center stage for the next decade in microelectronic technology.[21] As William Shockley contemporaneously declaimed in 1952: 'For the last few years, practically all advances at Bell Telephone Laboratories in transistor electronics and transistor physics have been based on the availability of single crystal material.'[22]

Scaling-Up Crystals: Texas Instruments

Between 1952 and 1955, Gordon Teal and William Shockley left the Bell Telephone Laboratories to start new semiconductor operations. Teal established the Central Research Laboratories of Texas Instruments, while Shockley formed Shockley Semiconductor Laboratory, a subsidiary of Beckman Instruments. Both Teal and Shockley were motivated, in part, by disappointments at Bell Labs. Teal had long-wanted to direct a more substantial group at the Labs. His superiors, who did not think that he was of management caliber, repeatedly refused him. The only way for Teal to go into research management was to join another firm. Similarly, Shockley had seen his career hopes hamstrung at Bell Labs. Conflicts within his group (mostly of Shockley's making) had convinced Bell Labs' top leadership that Shockley's management skills were limited. From then on, it was clear to Shockley that he would not go higher in the Bell Labs hierarchy. Leaving Bell Labs for new commercial organizations was also a means for Teal and Shockley to personally reap monetary reward for their work—certainly more than at Bell Labs where they had received limited financial consideration for their inventions.[23]

Perhaps most importantly, these men were interested in seeing their inventions used widely. Like many researchers at Bell Labs, they had been frustrated at the sluggishness with which AT&T, Bell Labs' parent company, introduced semiconductor electronics in its telephone systems. Rather than building telephone switching equipment around transistors, AT&T deployed a new generation of electromechanical devices. Additionally, anti-trust legal actions by the federal government precluded AT&T and its manufacturing arm, Western Electric, from participating in the electronic components market. The consent decree of 1956 that concluded these legal proceedings stipulated that AT&T focus solely on providing telephone services, and that Western Electric only manufacture the equipment used to do so. With this technical inertia and the looming legal restrictions, moving to Texas Instruments and Beckman Instruments was the best way for Teal and Shockley to bring the technologies they had helped develop to the open market.[24]

Texas Instruments' strategy for entering the semiconductor business was the mastery of the large-scale production of electronic materials. When Teal joined the firm in late 1952, Texas Instruments had rudimentary experience with electronic materials. The firm's origins were in the oil exploration business. For much of the 1930s, the corporation, then named 'Geophysical Service Inc.,' had produced and operated seismographs for Texas oil companies. During the Second World War, the firm diversified into airborne magnetometers for anti-submarine warfare. The firm then expanded into a variety of military systems and components in the immediate post-war period. At the center of this expansion strategy was Patrick Haggerty, an electrical engineer who joined the firm in 1945. Haggerty, a former Navy procurement officer, saw great potential in the military market. He was also interested in integrating vertically, moving from systems to the manufacture of electronic components.[25]

To establish itself in the semiconductor industry, Texas Instruments focused on *making* and *understanding* crystals. 'One of the convictions I had when we were making up our minds [about TI's program in solid state electronics],' Haggerty later recalled, 'was that the future of electronics was going to be heavily dependent upon the ability to understand and manipulate appropriate materials.'[26] Not only were semiconductor crystals central to device design and production, but they were also rare. No independent producers of semiconductor crystals had yet emerged. Thus, germanium and silicon crystals constituted a significant barrier to entry for the semiconductor business, as they were very costly and difficult to make. But, as a corollary, mastering their volume production could open up very significant business opportunities for Texas Instruments.

Haggerty organized two complementary crystal growing efforts at TI. First, engineers in the device development group within TI's manufacturing plant, who had attended Bell Labs' transistor symposium in mid-1952, replicated the crystal pullers that Teal had designed there for making germanium crystals (in 1951, TI purchased a transistor technology license from Bell Labs).[27] They improved on these crystal-growing techniques—particularly enhancing the precision of their operation. Using the resulting material, the development group made point contact germanium transistors and, starting in 1953, germanium grown junction transistors. Second, Haggerty hired Teal in December 1952 to establish Texas Instruments' Central Research Laboratories. The new laboratories focused on making silicon crystals, with the goal of continuing Teal's pursuit of silicon grown junction transistors. To produce high quality silicon crystals, Teal assembled a team of chemists and engineers, replicating the mix of his successful collaborations at Bell Labs. Among the new team's members were Willis Adcock, a chemist who had previously worked in the oil industry, and Morton Jones, a recent chemistry Ph.D. from Caltech. These men built on the silicon crystal work that Teal had accomplished in his last year at Bell Labs.[28]

Jones and Adcock's dual mission was to gain a better understanding of crystal growing techniques, and to use that understanding to create a production-worthy, grown junction silicon transistor. Much of their attention was devoted to new techniques for maintaining the high-perfection of silicon crystals while very carefully introducing impurities into the crystal melt in order to make NPN junctions. They focused on pulling crystals with thin junctions. By the spring of 1954, Teal, Jones, Adcock, and their co-workers had succeeded in making a grown junction silicon transistor. Haggerty later recalled: 'One day in April 1954, I got an excited call from Gordon Teal. I hurried over to the laboratory in which Willis [Adcock], Morton [Jones], and Jay [Thornhill] were working at turning single-crystal silicon into a transistor. I suppose that within 10 or 15 minutes of the time in which they had, in fact, succeeded, I was observing transistor action in that first grown-junction silicon transistor. By May 1954, we had produced modest quantities and Gordon Teal was able to make a dramatic announcement that the silicon transistor was in production at TI.'[29] It was a major coup for the semiconductor upstart. Teal announced this breakthrough at the meeting of the IRE National Conference on Airborne Electronics in May 1954. Silicon transistors were highly anticipated in aviation electronics circles, for their ability to operate at much higher temperatures than their germanium cousins could. Texas Instruments was the first firm to commercialize the silicon transistor.[30]

To consolidate their lead in silicon transistors, in the summer of 1954 Teal and Haggerty decided to start producing ultrapure, electronic-grade silicon, the starting material of the 'melt' used in pulling silicon crystals. Up to that time, TI, like Bell Labs, had relied on the chemical giant DuPont for its supply of electronic-grade silicon. Haggerty thought it imperative for TI to control its basic silicon supply and wanted the firm to produce high-purity silicon internally. 'Texas Instruments did not want to leave control of a vital aspect of its technology to outside suppliers,' an executive later summarized.[31] Teal then formed a new group around Adcock to devise economic ways of making electronic-grade silicon. Within two years, Adcock and his group developed a chemical reduction method for the production of electronic-grade silicon (which, echoing Teal's early Bell Labs work, used a tetrachloride decomposition). By 1956, the laboratory had designed and built a pilot plant for raw silicon production.[32]

As a result, TI became a major producer of both raw electronic-grade silicon and silicon single crystals. In 1957, it moved into the full-scale production of the raw electronic-grade silicon and started selling it on the open market. Six years later, in 1963, the firm edged DuPont, and several other early electronic-grade silicon producers, out of the market.[33] By the mid-1960s, Texas Instruments fabricated half of the total US production of raw electronic-grade silicon and was one of the three largest makers of silicon single crystals in the nation. More importantly, TI's advances in silicon crystals and silicon grown junction transistors enabled the firm to dominate the first years of the silicon device business. With a virtual monopoly on silicon transistors until 1958, TI benefited handsomely from the fast-growing military demand for the devices. Starting in mid-1950s, the Department of Defense encouraged military system firms to integrate silicon transistors into their products—as a means for improving the reliability of military equipment (silicon transistors could operate at higher temperatures *and* were more reliable than germanium transistors). TI's preeminent position in silicon transistors, and its establishment of a parallel line of germanium transistors, propelled the firm to predominance as the largest semiconductor manufacturer in the United States by the late 1950s and early 1960s.[34]

Learning from Failure: Shockley Semiconductor and Its Descendants

Silicon crystals also dominated the technical and business calculations of William Shockley. In 1955, Shockley left the Bell Telephone Laboratories to establish a new semiconductor firm, Shockley Semiconductor Laboratory, as a subsidiary of Arnold Beckman's Beckman Instruments, Inc. Shockley Semiconductor, located in Mountain View, California, was established to manufacture silicon transistors. To win competitive advantage in the silicon transistor business (TI had just introduced its first silicon transistor), Shockley oriented his firm around two new promising technologies: solid state diffusion and a novel approach to silicon crystal-making. Solid state diffusion had been developed at the Bell Telephone Laboratories and was used there by Morris Tanenbaum, a chemist, to fabricate a silicon transistor. Diffusion entailed the controlled introduction of impurities, in gas form and using high temperatures, into silicon crystals. Shockley expected the thin junctions that this process allowed would lead to higher frequency and faster switching transistors than those produced by TI. Moreover, diffusion was particularly well suited to the batch production of multiple transistors on a single silicon wafer. In such a batch production, yield—the proportion of working to non-functional transistors created on a single wafer—would be the key factor for economic competitiveness. Defects in the silicon wafers, be they crystalline faults or unwanted chemical impurities, would lower yields and thus were an object of concern. Therefore, in tandem with diffusion, Shockley was interested in following up on a new crystal growing technique that he had devised in collaboration with R. Victor Jones, a recent Ph.D. from the University of California, Berkeley whom Shockley had recruited. This new growing technique promised purer silicon with better crystalline structure and, thus, higher quality devices produced at higher yields.[35]

Shockley and Jones' plan for an improved crystal puller took aim at a major limitation of Teal's approach. In Teal's pullers, destructive contaminants found their way into the silicon crystal through both the melt and the growing process. These impurities came from the quartz crucible and from the outside air. Moreover, Teal's crystals contained crystal defects arising from temperature variations in the silicon melt. Shockley and Jones sought to solve these problems in their new crystal puller with three innovations. First, Shockley and Jones would largely eliminate contamination from the crucible by pulling their crystals from a pool of melted silicon atop a far larger block of pure silicon. This contrasted with Teal's machines, in which the silicon melt was in direct contact with the crucible. In order to heat the silicon block and create a puddle of molten silicon atop it, the pair devised a complex heating system. A 'bird cage' of three-phase molybdenum wire windings, held on a series of eight insulating rods of sapphire, provided the resistance heating for an 'oven' compartment in which the silicon block was heated to just below its melting point. At the same time, a ring-shaped resistance heater hung just above the surface of the silicon block, creating the puddle of silicon from which they would pull the crystal. The pulled crystal passed through the center of the surface heater ring, protected from the heat of the surface heater and the 'bird cage' by two heat shields. Second, Shockley and Jones would pull their crystals in a high vacuum to avoid contamination from the outside atmosphere. This was not an entirely new idea. Bell Laboratories' researchers had grown germanium crystals under vacuum, but this had never been done in silicon before. Finally, Jones and Shockley would use sophisticated temperature controls to produce more structurally perfect silicon crystals. For example, the top heater for the puddle was governed by an optico-electronic feedback system that constantly gauged the temperature of the puddle melt. In all, it was the most complex crystal puller ever devised to that point.[36]

It took Jones and at least three other Shockley recruits—Dean Knapic, Eugene Kleiner, and Julius Blank (all of whom were former Western Electric engineers)—nearly a year to refine this design and build the complex machine. Because of the importance that Shockley placed in this project, the group worked largely in isolation, sharing little of their work with their colleagues who were working on diffusion and transistor engineering in another part of the small lab. By the summer of 1956, the machine was readied for testing. It did not go well. In the words of Julius Blank, it was a 'major fiasco.' Soon after the team switched the machine on, it literally blew up. A major electrical short created a thunderous noise, violently tripping all of the facility's circuit breakers. The electrical transformer outside the laboratory was damaged as well, spraying oil that reportedly ruined the polishes of four cars parked underneath. The disaster led Shockley to all-but abandon the project. While the crystal grower was eventually modified and run, Shockley focused the laboratory on conventional crystal growing techniques. He laid aside his plan for gaining a competitive advantage over TI through new crystal growing techniques.[37]

The catastrophic test of the crystal growing project had many repercussions. It led to significant turmoil at Shockley Semiconductor. The crystal growing team disintegrated. Jones left for a teaching position at Harvard University before the crystal grower he had designed with Shockley was fully completed. Further, Shockley publicly fired Leo Valdes—an experienced transistor physicist whom Shockley had poached from Bell Labs—in front of other staff. Valdes had been enmeshed in crystal growing work, and many in the laboratory associated his firing with the setbacks to the general crystal production effort. This action, along with other examples of Shockley's heavy handedness, led several engineers and scientists on Shockley's staff to organize against him. The discontented were also motivated by Shockley's change in competitive strategy away from silicon transistors to more complex and speculative devices. Among the concerned were Gordon Moore, Sheldon Roberts, Jean Hoerni, Jay Last, Victor Grinich, Julius Blank, and Eugene Kleiner. These men contacted Arnold Beckman, Shockley Semiconductor's backer, and asked him to replace Shockley with a professional manager. When Beckman declined, the rebellious group (joined now by Robert Noyce, Shockley's director of research) quit in the fall of 1957 to start a new firm, Fairchild Semiconductor Corporation, with financing from Fairchild Camera and Instrument. Dean Knapic, who had hoped to join the Fairchild group but had been turned down, left to start his own company, Knapic Electrophysics, shortly afterwards. Knapic Electrophysics funded by several electronics entrepreneurs on the San Francisco Peninsula, was the first firm specializing solely in the making of silicon crystals in the US.[38]

Knapic established his firm on the basis of Teal's crystal pulling techniques. After the disastrous end of Shockley's crystal growing project but before his leaving Shockley Semiconductor, Knapic had been asked by Shockley to build crystal growers patterned on Teal's design (Shockley Semiconductor was a licensee of Bell Labs' transistor technology) at a separate facility in Mountain View. Knapic assembled a small team that built the pullers and made silicon crystals for Shockley. When Knapic left Shockley Semiconductor, he took much of his team with him and he recreated what he had done for Shockley at his new firm. However, he eventually developed crystal pullers on his own design that diverged significantly from Teal's techniques. By 1959, Knapic designed, and submitted a patent for, a crystal puller using resistance heaters. To combat contaminants from outside air, Knapic's machine blew a high-volume stream of hot, filtered inert gas over the crystal melt. Knapic also kept the pressure of inert gas inside the puller at a pressure above that of the exterior atmosphere. Any leaks would be from the inside out, preventing contamination.[39]

While Knapic Electrophysics addressed a real need for silicon crystals in the semiconductor industry, the firm lost money during its first years of operation. As a result, its funders closed the operation in 1962. Although Knapic Electrophysics was short-lived, it started a merchant silicon crystal industry on the San Francisco Peninsula. After Knapic Electrophysics' demise, one of its engineers, Robert Lorenzini, purchased some of the firm's equipment and started his own silicon crystal business, Elmat. He later formed Siltec Corporation, the crystal-making firm that was sold to Mitsubishi Metal in 1986.[40]

Like Knapic, the Fairchild group used more practical ways of making silicon crystals than the one Shockley had first imagined for Shockley Semiconductor. They urgently needed silicon crystal for the engineering and production of double diffused transistors at their new firm. This urgency and the related pragmatic approach to crystal production were derivative of the predominantly *manufacturing* orientation of the start-up. The eight co-founders of Fairchild Semiconductor created the firm with a single objective: to develop and manufacture, as quickly as possible, the diffused silicon transistor they had pursued at Shockley Semiconductor. Theirs was a race to market a device that the semiconductor industry had yet to produce. As such, their efforts were focused on the speedy establishment of manufacturing operations that would batch produce high-performance transistors with reasonable yields. At the top of their list of priorities was obtaining a supply of high quality silicon single crystals.[41]

Troublingly, few of the founders had prior experience with growing silicon crystals. Sheldon Roberts, the metallurgist in the group, was the only one who had grown crystals before working at Shockley, but these were of metal. At the request of Noyce, who had assumed the leadership of research at Fairchild Semiconductor, Roberts took up the task of making silicon crystals for the start-up. Noyce also suggested that Roberts develop a robust and practical crystal grower. This grower would follow Teal's general design. However, Roberts used resistance heating instead of the more 'high-tech' RF induction heating that Teal and his followers had used. For Noyce and Roberts, resistance heating held several advantages over RF induction heating. Because they dispensed of the need for expensive RF generators, resistance heaters were cheaper, easier to maintain, and safer to operate than pullers using induction heating.[42]

In 1957 and early 1958, Roberts hired technicians with germanium crystal growing experience and came up with a new crystal puller design. Roberts' crystal puller produced high quality silicon crystals and was considered a trade secret by the management of Fairchild Camera and Instrument, Fairchild Semiconductor's parent company. Roberts' crystals were soon put to use by his colleagues in device design and production. Roberts also supervised the construction of an array of crystal pullers to be run in Fairchild's manufacturing plant. These growers supplied all the crystals that Fairchild employed in both R&D and production in 1958 and 1959 (it was only in 1960 that Fairchild started to complement its internal production with silicon crystals from Knapic Electrophysics, Monsanto, and other merchant suppliers).[43]

Fairchild Semiconductor's fashioning of robust, practical approaches to producing silicon crystals enabled the firm to be the first to develop and market two major microelectronic devices—the double diffused planar transistor and the integrated circuit. In both cases, the Fairchild group exploited one of the natural properties of silicon crystal—namely the ready formation of a layer of silicon oxide on the crystal when it is exposed to oxygen (especially at high temperatures). In 1955, Carl Frosch at Bell Laboratories discovered that this layer of silicon oxide could be used as a 'mask' for dopant diffusion into particular areas of the crystal. Another group at Bell had also found that a thermally grown oxide layer passivated, or electrically stabilized, the crystal surface. While at Shockley Semiconductor, the physicist Jean Hoerni, along with Gordon Moore and Robert Noyce, had experimented with silicon oxide layers and found that a 'clean' oxide layer over the junction between the base and the emitter regions of a transistor would reduce leakage or, in other words, diminish an undesired reverse flow of electrons at the junction. Following up on this work at Fairchild, the trio developed a transistor for which the oxide layer was left on top of the emitter junction after processing. They discovered that this new device had much improved electrical parameters.[44]

Building on these results, in 1959 Hoerni developed a new manufacturing process, the planar process, which used both the masking and the passivating properties of oxide layers on silicon crystals. Indeed, the main approach of the planar process was to grow a layer of silicon oxide on top of the silicon crystal. Hoerni then used this layer to control the formation of the transistor structure by diffusion steps. Importantly, he left the oxide layer on top of the wafer after this processing. This went against all accepted knowledge in the silicon community: at the time, it was uniformly believed by practitioners of the silicon art that that an oxide layer used to mask dopants was 'dirty' and, therefore, had to be removed. Instead, Hoerni left the oxide layer on top of the wafer. He then made the startling discovery that, far from contaminating the crystal, the oxide passivated the transistor surface and protected the junctions from outside contaminants. This new transistor—the planar transistor—was widely superior to other double diffused silicon transistors. It had much improved electrical characteristics and was extremely reliable.[45]

Robert Noyce went one step further in the exploitation of silicon oxide layers. In addition to masking dopants and passivating crystal surfaces, silicon oxide layers are electrically insulating. Noyce perceived that an oxide layer could insulate the underlying crystal from a network of aluminum lines deposited on top of the oxide. This use of the crystals' oxide layer was the basis for Noyce's major device innovation: the integrated circuit. His idea was to create various planar transistors, diodes, resistors and capacitors on the same silicon wafer, to form isolation regions between them, and then to deposit a patterned film of aluminum on top of the oxide layer to make electrical contacts between the various devices in the same wafer. This idea was put into silicon by Jay Last, another member of Fairchild's founding group, in 1960. These major innovations, the planar process and the integrated circuit, grounded in silicon crystal experience, transformed Fairchild into the second largest producer of silicon devices after Texas Instruments in the first half of the 1960s.[46]

Conclusion

Single crystals of germanium and silicon were primary to microelectronic device development as well as business strategy in the crucial, opening two decades of the semiconductor industry. Single crystals enabled the development and manufacture of a vast array of microelectronic devices. Innovations in and capacities for single crystal production were key determinants of firm success, and thus shaped the semiconductor industry in its formative years. Innovation in single crystal production underpinned Bell Telephone Laboratories' remarkable flurry of microelectronic device firsts in the late 1940s through the middle 1950s. As Walter Brattain noted in 1955, 'The progress achieved in semiconductor research in the past few years is closely associated with … advances in the preparation of materials. The availability of such pure and single crystals as we have in present-day silicon and germanium amounts to a revolution in the physics of solids.'[47] Bell Labs structured the emerging landscape of the semiconductor industry by the wide dissemination of its single crystal and microelectronic device innovations through broad licensing of its patents.

Texas Instruments' strategy for entering this industry went beyond licensing Bell Labs' patents, and focused on the fundamental importance of single crystals. TI recruited Bell Labs' single crystal pioneer, Gordon Teal, to establish a new central research laboratory devoted to semiconductor materials. Through a strategy of scaling up, both in the manufacture of raw electronic-grade silicon and silicon single crystals, TI achieved early, and lasting, dominance in the semiconductor industry. At Shockley Semiconductor Laboratory, William Shockley made single crystal innovation a fundamental initial strategy for competing in the silicon transistor business. The failure of this strategy, and Shockley's subsequent reorientation toward highly experimental new device types, led to the disintegration of the firm.

Learning from the failure of Shockley Semiconductor, Dean Knapic, in his Shockley spin-off Knapic Electrophysics, began a process of disaggregation in the semiconductor industry. He concentrated solely on the *production* of silicon single crystals, offering his customers, the *users* of single crystals in making devices, a competitive edge in materials and the ability to focus more on device design. Like Shockley Semiconductor, Fairchild's initial strategy for entering the semiconductor industry was grounded in the conviction that single crystals were essential to doing *anything* in microelectronics. Arising from the Fairchild founders' experience of the failure of Shockley Semiconductor, the firm emphasized a manufacturing orientation, and developed a single crystal production capability with a robust, low-cost, 'good enough' approach. Fairchild's experience with single crystals, and in particular its attention to the crystals' ready formation of oxide layers, drove the firm's two groundbreaking device innovations: the planar transistor and the integrated circuit. These device innovations, in turn, propelled Fairchild to a leading position in the semiconductor industry.

During this formative period, the coupling of single crystal production with device development at Bell Labs, TI, and Fairchild led to a preponderance of non-physicists and non-electrical engineers in the creation of microelectronic technology. Many key actors were chemists, metallurgists, and mechanical engineers: the likes of Gordon Teal, Morgan Sparks, Morris Tanenbaum, Willis Adcock, Morton Jones, Gordon Moore, C. Sheldon Roberts, John Little, Ernie Buehler, and Dean Knapic. These men worked in institutions that were profoundly shaped by their customers' needs. These customers ranged from AT&T's internal systems and manufacturing arms, to the manufacturers of end products serving both military and consumer markets. In this way, the crystal makers' world was bound up with the expansion of both military technology and consumer culture across the Cold War.

In the 1960s and afterward, silicon crystals were no less critical to microelectronic technology; but there was a continuing decoupling of crystal-making and device development, with the emergence of a merchant silicon crystal industry that began to make most of the innovations in silicon growing and moved to occupy the specialized niche of manufacturing increasingly large-diameter wafers of ultrapure and structurally perfect silicon crystals. In the 1960s and 1970s, the merchant production of silicon single crystals grew enormously, allowing the expansion of integrated circuit manufacturing. The sales volume of integrated circuits grew from US$5 million in 1961 to US$1.3 billion in 1976, leading to an extraordinary increase in the consumption and therefore production of silicon crystal. Silicon crystal production grew from 0.15 million in^2 of silicon wafer in 1961 to 140 million in^2 in 1976—an increase of three orders of magnitude in 15 years.[48]

With the rise of the merchant crystal industry, the manufacture of silicon crystals became a less visible concern inside semiconductor firms. For these firms, miniaturization pushed the loci of learning and innovation farther down the integrated circuit fabrication process. To produce increasingly dense and powerful integrated circuits, semiconductor firms focused on *processing* silicon crystals rather than *manufacturing* them. For example, in the early 1960s the Bell Telephone Laboratories, Motorola, and Fairchild Semiconductor developed epitaxy, i.e. techniques for the deposition of a layer of single silicon crystal on top of the silicon substrate. Epitaxy offered a new way of electrically isolating transistors in the same chip and thereby improved the electrical characteristics of integrated circuits. Considerable efforts and resources were also devoted to the control of the vertical and lateral dimensions of semiconductor devices, especially through advances in photolithography and the development of new doping techniques such as ion implantation. All these techniques, however, had one attribute in common: they were about the careful control of the electrical characteristics of silicon single crystals. Far from being 'dematerialized,' microelectronics is an intensely material technology—one that relies on complex materials and intricate ways of manipulating them.

While this 'materials centered' approach has direct utility for a full accounting of the history of microelectronics, we suggest that it also holds broader promise for understanding other technologies. Recently, one of the most discussed methodological issues in the history of technology has been the extent to which contemporary scholarship is 'over' or 'under socialized,' in reference to the social construction of technology approach.[49] Our 'materials centered' approach indicates that the history of microelectronics, and perhaps many other areas of recent scholarship in the history of technology, is 'under materialized.' That is, this scholarship underemphasizes materials as an analytical category in its accounts of technological developments. A renewed emphasis on materials leads to new questions. The standard lines of inquiry remain—unpacking design, interrogating actual use, and exploring social and political contexts and consequences. To these lines, 'materialized' accounts address new questions: 'From what were artifacts *made*?' 'Who supplied the materials?' 'What were the social, political, and economic contexts for this network of materials-supply?' 'How were materials used and integrated into production systems?' 'How did materials and material capabilities shape design, manufacturing, and the innovation process?'

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Notes

[1] Pollack, 'Mitsubishi to Acquire Siltec.'

[2] Robertson, 'At Dawn We Slept.'

[3] Hoddeson, 'Entry of the Quantum Theory;' Hoddeson, 'Discovery of the Point-Contact Transistor;' Hoddeson *et al.*, *Out of the Crystal Maze*; Riordan and Hoddeson, *Crystal Fire*. For an exemplary device design centered account with a more integrated treatment of materials, see Bassett, *To the Digital Age*. A manufacturing centered account giving some treatment of materials may be found in Leslie, 'Blue Collar Science.'

[4] Recent efforts in the history of modern biology and of scientific experimentation have demonstrated the importance of materials to understanding the historical dynamics of these domains. For entrée into the material-centered literature in the history and philosophy of scientific experimentation, see Radder,*The Philosophy of Scientific Experimentation*; Baird, *Thing Knowledge*; Galison, *Image and Logic*; Wise, *The Values of Precision*. For examples of widely-read 'classics' from the science studies literature that demonstrate that socialized and materialized accounts are not contradictory, but are rather quite complementary, see Latour

and Woolgar, *Laboratory Life*; Shapin and Schaffer, *Leviathan and the Air-Pump*; Collins, *Changing Order*. A well-known demonstration that socialized and materialized accounts can be blended successfully in more broadly accessible registers as well is Kidder, *Soul of a New Machine*. For a different take on 'materialization' in the history of science, in which the bodies of social actors are given direct attention, look to Lawrence and Shapin, *Science Incarnate*. Andrew Pickering's concept of the 'mangle of practice' for the understanding of the history of science accords very well with the intermixing of socialized and materialized perspectives this study advocates for the history of technology. Indeed Pickering's mangle is perhaps even more suited to the analysis of the history of technology, in both its ideational (knowledge and design) and performative (functional behavior) aspects. For a broadly accessible articulation of the mangle, see Pickering, 'Mangle of Practice'. For an extended treatment, see Pickering, *Mangle of Practice*. Within the history of biology and the life sciences, exemplars and sources for further references within the material-centered vein include Kohler, *Lords of the Fly*; Rheinberger, *Toward a History of Epistemic Things*; Clarke and Fujimura, *The Right Tools*; Rader, *Making Mice*; Creager, *Life of a Virus*.

[5] For a discussion of internal firm competencies as a determinant of economic performance in the semiconductor industry, see Holbrook *et al.*, 'Nature, Sources, and Consequences.' Of note, materials-linked capacities are absent from the account.

[6] Teal, 'Single Crystals of Germanium and Silicon.'

[7] For details, see Teal's numerous patents from the 1930s on television camera tubes and photodetectors: US Patent numbers 2,160,796; 2,160,797; 2,160,798; 2,217,334 (Diggory and Teal); 2,188,940 (Diggory and Teal); 2,196,278; 2,160,799; 2,236,041; 2,245,624; 2,200,722 (Pierce and Teal); and 2,217,168 (Hefele and Teal). An exemplary example is Teal's patent number 2,173,923, filed in 1936 and granted in 1939.

[8] In 1940, US–British radar development efforts used semiconductor crystals to create receiving components suitable for microwave radar systems. At Bell Laboratories, crystal rectifiers had been identified as a promising line of inquiry though work there in the late 1930s on experimental microwave radar systems and high frequency radio communications. The British radar establishment focused on semiconductor crystal receiving components as the result of a review of the scientific literature. In early 1941, the British organization communicated its successes in the production and use of semiconductor crystal rectifiers in radar systems to its US counterpart. The performance of these crystal rectifiers led to an intensification in the study and production of them at a number of US sites, including Bell Labs. While certain features of the packaging of crystal rectifiers were transferred from the British effort to Bell, the optimal materials for and design of crystal rectifiers for various military radar systems remained very much an open issue. For a history of these developments, see Buderi, *The Invention*, especially chapter 15, 308–333.

[9] Teal, 'Method for Producing Rectifiers.'

[10] Goldstein, 'Finding the Right Material,' 97–99.

[11] Teal, 'Single Crystals,' 623; Goldstein, 'Finding the Right Material,' 102. In this vacuum tube model, Teal may have considered the work of Irving Langmuir. Langmuir had been trained as a physical chemist before becoming a key researcher at General Electric, and had won the Nobel Prize in chemistry in 1932. Langmuir's high-vacuum studies were hailed as a key to General Electric's position in the vacuum tube industry. For an excellent review of Langmuir's career, see Reich, 'Irving Langmuir and the Pursuit of Science and Technology in the Corporate Environment.'

[12] Teal, 'Single Crystals,' 623.

[13] Ibid.

[14] Scheel, 'Historical Aspects;' Hoyem and Tyndall, 'An Experimental Study.'

[15] Little and Teal, 'Production of Germanium Rods;' Teal and Little, 'Growth of Germanium.' On the subject of Teal's use of hydrogen as the interior atmosphere for his crystal puller, this choice may very well have been guided by Teal's chemical investigations of germanium as a

graduate student at Brown. In fact, Teal had studied germanium–hydrogen compounds and their reactions. (See the material from his dissertation, published in Teal and Kraus, 'Compounds of Germanium.') Bathing the growing germanium crystal in hydrogen acted to *increase* its chemical purity due to hydrogen's propensity to combine with, and hence trap, various unwanted impurities in the system, as well as to reduce, and thereby remove, oxides of germanium. Similarly, Teal and Little often introduced water vapor into their hydrogen gas mix to combat chemical impurities and germanium oxide formation. In addition to their use of this reducing hydrogen atmosphere inside their crystal puller, Teal and Little grew single crystals of germanium within a chemically inert atmosphere of nitrogen. See Lawson and Neilsen, *Preparation of Single Crystals*, 91.

[16] Haynes and Shockley, 'Investigation of Hole Injection;' Riordan and Hoddeson, *Crystal Fire*, 170–1.

[17] Shockley *et al.*, 'Hole Injection;' Teal, 'Single Crystals,' 625.

[18] Shockley, 'Theory of P–N Junctions.'

[19] Teal, 'Methods of Producing Semiconductive Bodies;' Sparks, interview.

[20] Teal and Buehler, 'Growth of Silicon;' Buehler, 'The First Czochralski Silicon.'

[21] Tanenbaum, interviews; Sparks, interview; Goldey, interviews; Hall and Dunlap, 'P–N Junctions;' Hannay, 'Recent Advances in Silicon;' Scaff and Theuerer, 'Semiconductor Comprising Silicon;' Fuller and Ditzenberger, 'Diffusion of Boron.'

[22] Shockley, 'Transistor Electronics.'

[23] Sparks, interview; Riordan and Hoddeson, *Crystal Fire*, 225–237.

[24] Goldey, interviews.

[25] Johnson, 'Opening Remarks;' Haggerty, 'A Successful Strategy;' Green, interview.

[26] Haggerty, 'A Successful Strategy.'

[27] The device development group, like Teal at Bell Labs, used hydrogen as the interior atmosphere of their crystal puller. They also obtained germanium single crystal seeds from Bell. Teal, 'Technical Highlights of TI.'

[28] Haggerty, 'A Successful Strategy;' Adcock, 'Growing the First TI Silicon Crystal;' Teal, 'Technical Highlights of TI.'

[29] Haggerty, 'A Successful Strategy.'

[30] Jones, 'Research notebook entry;' Teal, 'Technical Highlights of TI;' Jones and Adcock, 'Grown Junction;' Adcock *et al.*, 'Silicon Transistor;' Haggerty, 'A Successful Strategy;' Teal, 'Announcing the Transistor.'

[31] Sangster, 'Creating the Materials.'

[32] Haggerty, 'A Successful Strategy;' Adcock, 'Growing the First TI Silicon Crystal;' Sangster, 'Creating the Materials;' Teal, 'Technical Highlights of TI;' Pirtle, *Engineering the World*.

[33] Silicon was at the core of TI's business, and thus the firm had several reasons to pursue the manufacture of raw electronic-grade silicon in addition to single crystal material. For DuPont, electronic-grade silicon was but one of some 1200 chemical products offered by the industrial giant. Further, electronic-grade silicon was, for DuPont, a relatively small market. The total value of all electronic-grade silicon produced in the USA in 1963—including both polycrystalline raw silicon and single crystal material—was US$11.2 million. This was a market of a size under 2% of DuPont's sales for the *first quarter* of 1963. For reasons of competition and corporate focus, the early silicon producers like DuPont and Merck yielded to rising new producers like TI. See US Bureau of Mines, *Minerals Yearbook 1963*, 993; Rutter, 'DuPont Gaining Despite a Loss.'

[34] Sangster, 'Creating the Materials;' Teal, 'Technical Highlights of TI;' McDonald, 'The Men who Made TI' and 'Where Texas Instruments Goes from There;' 'Silicon Sales Should Rise by 50% in 1967,' *Chemical and Engineering News*, 22–23.

[35] In 1955, Shockley sought to buy crystal pullers from Texas Instruments—to no avail. Haggerty refused to sell him crystal growers. 'Unfortunately,' Haggerty wrote to Shockley, 'it is with regret that I must advise you that we still feel it would unwise for us to sell pullers.'

Haggerty, Letter to Shockley. In 1955 and 1956, Shockley acquired silicon single crystal material on an informal basis from the Bell Telephone Laboratories and from one commercial supplier of this material. This supplier, the Sarkes Tarzian Company of Bloomington, Indiana, would occasionally make silicon crystal available for open sale. Sarkes Tarzian, initially a radio manufacturer, produced silicon material in Bloomington for the production of silicon rectifiers used in its own products. Blank, interview; Finn and Parsons, 'Some Basic Physical Properties of Silicon;' 'Big TV Operation Began in Bindery,' *New York Times*; Jones, interview.

[36] Shockley and Jones, 'Crystal Growing Apparatus;' Jones, interview.

[37] Roberts, telephone conversation; Grinich, interviews; Blank, interview.

[38] As Julius Blank recalls, Valdes was the major focus of Shockley's ire, in part, for his insistence on the use of sapphire for the insulating rods of the 'bird cage' resistance heater in the crystal grower. Jones had determined that the cause of the disastrous short was the weakening of the sapphire rods at high temperatures. This weakening allowed the molybdenum wires to sag and make electrical contact with the metal body of the crystal grower. However, Jones himself recalls events differently. Jones holds that Valdes was never involved with the Shockley–Jones crystal grower, and that his employment was terminated for quite separate reasons. Jones does recall that Valdes was involved with conventional crystal growing efforts. In any case, several members of the laboratory associated Valdes' firing with the profound setbacks to the crystal growing effort. Blank, interview; Jones, interview; 'Missile, Satellite Improvement Promised by New Transistor Crystals, Company Says,' *Daily Palo Alto Times*; Lécuyer, *Making Silicon Valley*, 133–139.

[39] Grinich, interviews; Roberts, telephone conversation. Even before the disastrous end of the Shockley–Jones designed crystal grower, Knapic was involved with Gordon Teal's type of crystal grower. Knapic supervised Julius Blank and Eugene Kleiner at Shockley Semiconductor. As the development of the Shockley–Jones grower dragged on, Blank and Kleiner built a conventional crystal grower like Teal's (using induction heating and an internal atmosphere of inert gas rather than a high vacuum) at Shockley Semiconductor. This conventional crystal grower was a basis for Knapic's subsequent efforts at Shockley Semiconductor and in the early days of Knapic Electrophysics. Blank, interview; Knapic, 'Crystal Growing Furnace;' Knapic's crystal grower designs from the late 1950s may have benefited from his experience at Shockley Semiconductor as well. Knapic was the supervisor of Julius Blank at Shockley Semiconductor when Blank worked on a prototype resistance heater for crystal growing in 1957. Blank, interview.

[40] Lorenzini, interview.

[41] Moore and Last, interview.

[42] Roberts, telephone conversation; Humeny, conversation. Noyce may have been exposed to the idea of resistance heating at Shockley Semiconductor. In June 1957, William Shockley noted in his notebook that RCA and Pacific Semiconductors used resistance heating in their crystal growers. Shockley may have passed this information to Noyce. Shockley, Notebook titled 'Trouble.' Noyce may also have been exposed to the resistance heating approach through knowledge of the failed Shockely–Jones crystal puller or of Julius Blank's resistance heater prototype. Gordon Teal initiated a tradition for the use of induction heaters in crystal pulling through in his initial crystal puller of 1949; Bell Laboratories' researchers had considered the option of using resistance heaters in the middle 1950s. While resistance heaters would no doubt have been cheaper and more robust, Bell Laboratories saw two key advantages with induction heaters: they offered near instantaneous control response and they did not introduce contaminants. The comparative sluggishness of resistance heaters made temperature control more difficult, and the heated insulation materials that resistance heaters required posed contamination problems. See Bradley, 'Preparation of Germanium,' 139.

[43] Roberts, telephone conversation; Humeny, conversation; Last, Personal notebook. As he had at Shockley Semiconductor, Julius Blank played an important part in the actual fabrication

and hands-on design of the new resistance heating crystal growers at Fairchild Semiconductor. For Roberts, Blank created three-phase resistance heaters for the new growers, thereby approaching the type of temperature control and response afforded by the Teal-type, conventional induction heating growers. Further, Blank consciously 'over designed' the new Fairchild growers to render them extremely robust for continuous operation. In particular, Blank employed 'over powered' variable speed motors to drive the pulling rods and, with Victor Grinich, replaced many of the electrical components in the temperature control systems with upgraded, higher rated parts. Blank, interview.

[44] Lécuyer, *Making Silicon Valley*, 148–154.

[45] Hoerni, 'Planar Silicon Transistors;' Hoerni, 'Method for Manufacturing;' Lécuyer, *Making Silicon Valley*, 148–154.

[46] Noyce, 'Semiconductor Device;' Lécuyer, *Making Silicon Valley*, 155–164.

[47] Pearson and Brattain, 'History of Semiconductor Research.'

[48] 'Data from Monsanto,' Gordon Moore Papers. Attention to semiconductor crystals was also central to the formation of a new academic discipline, materials science and engineering, in the 1960s. For the history of materials science and engineering, see Bensaude-Vincent, 'The Construction of a Discipline.'

[49] The usage of the terms 'oversocialized' and 'undersocialized' accounts follows that coined in Scranton, 'Missing the Target?' For an overview of contemporary discussions in the history of technology community about the 'over' or 'undersocialization' of recent scholarship—and the specter of technological determinism that lurks behind these exchanges—look to Constant, 'Reliable Knowledge;' Williams, 'All That Is Solid;' and Ceruzzi, 'Moore's Law.'

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