Diversity, Complementarity, and Cooperation

Materials Innovation in The Semiconductor Industry

by Daniel Holbrook[1]

Historians and other scholars have convincingly portrayed the development of the transistor as the product of research in multiple disciplines conducted in both academic and industrial laboratories. Historian of physics Charles Weiner succinctly summarized the accomplishment of John Bardeen, Walter Brattain, and William Shockley, the Bell Laboratories' trio credited with the 1947 invention of the transistor as "emerg[ing] from a complex interaction of individuals, ideas, and institutions."[2] The three benefited from over twenty years of research in semiconductor materials, which in turn depended on advances in theories of solids, most notably the quantum theory of solids developed principally in Europe in the 1920s and 1930s.[3]

Contemporaries recognized this developmental dynamic as well. The editor of the November 1952 issue of *Proceedings of the IRE* commented specifically on the cumulative aspects of the transistor's invention, noting the contributions of a diverse set of scientists and engineers working in the service of both scientific and industrial projects.[4] And William Shockley himself acknowledged that the discovery of the transistor was far from an independent event. Rather it depended on a long series of previous inventions and theoretical developments.[5]

As the semiconductor industry grew and its product lines expanded, the same dynamic remained in operation. Commenting on the development of the monolithic integrated circuit (IC), one of the men credited with its invention, Jack Kilby of Texas Instruments explained that "progress [in ICs] is not the work of any single individual or small group of individuals. It has come about because of the contributions of thousands of engineers and scientists in laboratories and production facilities all over the world."[6] Industry historian Ernest Braun writes in a recent volume that innovation in solid-state electronics has been marked not so much by "great men and women and their glorious deeds" as by "superb efforts by great teams and many individuals within them," employed by academic laboratories and firms large and small.[7] All these observations acknowledge the importance of contributions from diverse disciplines and sites to the overall development of semiconductor technology.

How is this diversity of activities linked to larger processes of technological change? In recent years, historians and other academics have turned to variation and selective retention models of technological development. Historians George Basalla and Joel Mokyr, for example, both offer such models to explain the development of technologies.[8] Economists Richard Nelson and Sidney Winter offer a variation and selective retention model that seeks to explain the dynamics of economic growth under an industrial capitalist system.[9] While these authors and others using the so-called "evolutionary" models—with their invocation of the concepts familiar from classical biological evolutionary theory—recognize that diversity is important, they tend, nonetheless, to focus on the selection half of the model and to neglect the sources of the variations on which their selection mechanisms operate. These theorists simply assume that variation or diversity is an inherent part of the world, whether natural or man-made. They focus instead on the selection processes.[10] Little emphasis is placed on the existence of diversity among firms in an industry or on how and why such diversity may be important when technological development takes place mostly through the efforts of firms.[11]

To demonstrate the contribution of diverse sets of technological and scientific knowledge to the overall advance of semiconductor technology, this article examines two different materials used in the semiconductor industry. It first focuses on Shockley Semiconductor Laboratories' efforts to develop new means of producing device-grade — that is, ultra-pure — silicon. It then looks at research efforts at Fairchild Semiconductor Corporation concerning another important though less-examined material, photoresist.[12] Finally, the article briefly outlines the importance of diversity in the development of other chemicals used in the semiconductor industry. In each case diverse skills and knowledge that resided outside of the firm were needed to advance the work within the firm. This sort of diversity, which I will call complementary diversity, is frequently found in cases where the technology is particularly complex and thus requires knowledge from different disciplines and/or industrial sectors. Complementary efforts also often occur in situations where a material or process from one industry gets adopted by another, and the adaptation to the new application requires that knowledge from the supplier industry and knowledge from the user industry be brought together.

Materials and Devices in the Semiconductor Industry

No area was more basic to the success of the semiconductor industry and its technology than materials. Properly functioning transistors and other solid-state electronic devices depended on precise control of the composition and geometry of their constituent materials. The semiconductor industry required materials of much greater purity than any other contemporary industry.[13] The tight connection between structures and materials had marked consequences for solid state electronic devices and greatly influenced the course of research in the industry.

The semiconductor industry used more than just the elemental and compound semiconductor materials that formed the basic device structures. Richard Petritz, a contemporary semiconductor scientist, commented that "the processes used for manufacturing devices are sophisticated combinations of diverse technologies."[14] Various chemicals, plastics, metals, ceramics, and glasses were essential to the manufacture and operation of semiconductor electronic devices.[15] During the 1950s, as solid state electronics technology developed, research in all of these materials areas contributed to the technology's advance.

A constellation of manufacturers and suppliers engaged in materials research. Innovation in this area, however, relied on complementary research rather than simply competitive or mutually exclusive efforts, and many developments depended on adoptions from other technological areas. Metals, glasses, process- and photochemicals, plastics, and ceramics all came from other industries with existing networks of suppliers and researchers. The complementary nature of those networks and technologies for semiconductor manufacturing fed the development and manufacture of transistors and other solid state devices. A high degree of cooperation thus characterized this particular aspect of the technology's development.

This situation is, of course, somewhat to be expected. Since many of the materials used for semiconductor device manufacture were adopted from other industries and processes, a considerable amount of relevant knowledge already existed. Required adaptive research could be extensive or minimal but in either case was often best performed by those entities having the greatest existing knowledge. Communication and cooperation between users and suppliers frequently led to such research being performed by the suppliers.[16]

Complementary efforts between otherwise competing firms did not as a rule take place within explicitly coordinated or formalized programs. Rather, the complexity of the technology and the different histories of the individuals and firms involved helped establish patterns and networks for the exchange of technical and scientific information.

The interdisciplinary nature of semiconductor work was clear from the beginning of Bell Telephone Laboratory's post-war semiconductor research program. Bell Labs' efforts utilized the knowledge and skills of several different scientific and engineering fields, including metallurgy, physics, and chemistry.[17] Further developments in the technology continued to depend on such interdisciplinary endeavors. The production of semiconductor devices developed into a complex system of interrelated technologies. Chemical, thermal, optical, and physical processes all had their places in the manufacturing procedure. Developers of both products and processes continued to need knowledge from these disparate areas.

Even the largest and most broadly competent firms in the industry had to rely on other organizations for some needs. Bell Labs, for example, had its own metallurgists, chemists, physicists, and engineers of various stripes, but utilized researchers from academia and other firms as well as expertise from its materials suppliers to further its semiconductor research.[18] The smaller semiconductor firms founded in the 1950s could not hope to muster the resources needed to develop all facets of the complex technology. For firms such as Shockley Semiconductor Laboratories and Fairchild Semiconductor Corporation the complexity of the technology demanded cooperation with other research organizations.

Still, even small firms performed some research and development work. Their research agendas differed from those of larger firms due to their different histories as well as of the perspectives of their founders and managers. Thus one source of diversity was the existence of a relatively large number of firms, each of which possessed particular capabilities and viewpoints.

Aiding the dissemination of complementary knowledge was the fact that many of the founders and managers of early semiconductor firms were trained as scientists, and relatively free and open exchange of research results is a foundation of the scientific ethos.[19] Managers and researchers in the science-rich semiconductor industry adhered to this ethos, though it was somewhat modified by business competition.[20] The scientists' general willingness to exchange information, combined with the cooperation required by the heterogeneous nature of the production process, created an industry marked by active and widespread interchanges of technical and scientific data using both formal and informal information exchange networks.[21]

During the early years of semiconductor technology, technical complexity fostered cooperation between firms possessing complementary knowledge and research assets. Both large and small firms needed to rely on the knowledge and skills of other firms. Whether complexity makes complementary research agendas more *likely* is not clear; it seems, however, to make complementary efforts more *necessary*.[22]

Entries in *Industrial Research Laboratories of the United States* for the late 1950s and early 1960s indicate that materials technologies research commanded the interests of firms who were also listed as doing electronics research.[23] These included independent research labs (for example, General Laboratory Associates); laboratories of large manufacturing and chemical companies (such as those attached to General Electric, North American Philips, General Tire and Rubber, DuPont, Union Carbide and Carbon); research labs of large firms (Westinghouse, AT&T); and those of small firms (Vitramon, Inc., Electronic Transformer Co.). Automotive firms, chemical firms, electrical equipment manufacturers, instrument companies and others, in addition to semiconductor manufacturers, all listed themselves as doing some type of materials research.

Table 1:
Electronics firms performing materials research: 1956, 1960, 1965

	1956	1960	1965
"Electronics" firms	147	172	156
Materials R&D	27	54	59
Percent	18.4%	31.4%	37.8%

Source: Industrial Research Labs of the United States 1956, 1960, 1965.

The data in Table 1 reveal the increasing importance to electronics firms of materials research. For 1956, 27 electronics firms (18.4%) indicated that they performed some level of materials research. In 1960, 54 firms (31.4%), responded that they performed both electronics and materials research; by 1965 the number of such firms climbed to 59 (37.8%).[24] The types of materials technologies being researched remained largely consistent and concentrated around semiconductor materials, structure and purity of crystals, magnetic materials, dielectrics and insulators, ceramics and vitreous materials, and quartz and carbon materials and containers.

Each of the above research areas could provide illustrations of the contributions of diverse sets of expertise to overall technical advance. Here, however, we will examine particular events at the R&D laboratories of Shockley Semiconductor Laboratories (SSL)[25] and Fairchild Semiconductor Corporation (FSC) to show how the efforts of different firms combined to improve manufacturing processes as well as the performance of the devices themselves.[26]

The Development of Materials Science

The post-war development of materials science as a distinct and officially recognized field coincided almost exactly with the development of the semiconductor industry. A brief review of the emergence of materials science itself, then, is the most logical starting point for the exploration of complementary and cooperative research patterns.

Government funding for research on materials increased dramatically in the 1950s, as it did for many types of research. Increasing emphasis on and greater definition of solid state physics, which had begun in the pre-war years, continued. Cold War concerns about declining funding for basic science research in the United States, amplified by the vigor of government reaction to the Sputnik launch, led to the formation of university-based research centers devoted to interdisciplinary solid state research.[27] The new "materials science" explicitly addressed issues of improvements in materials, which had become "the limiting factor" in a number of crucial military equipment areas, including semiconductor electronics.[28] Materials science was a "union of physicists, chemists, and metallurgists" whose areas of research overlapped and intermixed, with "a stress on practical applications."[29] Materials science directly related to the semiconductor industry was no different, though basic science played a lesser role while empirical research played a larger one.

Solid state physicists' application of theory to the creation of useful devices fostered the tight intellectual and financial connections between materials science and industry.[30] Many advances in materials technologies came from empirical work in problem-oriented industrial labs operating under economic and corporate constraints rather than from the basic scientific research more typical of academic laboratories.[31] Semiconductor manufacturers certainly shared in the results of university research, but academia's role in semiconductor materials science declined as industrial labs increasingly dominated materials research in the industry.

Semiconductor Materials

Semiconductor materials research received a strong boost during the war.[32] University and industrial researchers who were pursuing more sensitive detectors for radar performed extensive investigations into germanium and silicon. Wartime solid state research established strong contacts between universities and industrial firms. During the war, Frederick Seitz of the University of Pennsylvania utilized DuPont's interest and expertise in high purity silicon;[33] likewise Karl Lark-Horovitz at Purdue worked with the

Eagle-Picher Company on high purity germanium.[34] Silicon diodes made from DuPont silicon were manufactured during wartime by Westinghouse, Sylvania, GE, and others.[35]

The almost immediate post-war discovery of the transistor reinforced the existing interdependence between materials research and device design and construction. Researchers had to meet two goals: regularity of crystalline structure and the precise introduction of selected impurities. Since the proper functioning of semiconductor devices depended on the crystalline structure of the material, control over it became essential. At the same time, William Shockley's 1949 junction transistor theory brought a new problem into focus—the selective addition of specific elements to the semiconductor material, or "doping." Thus, both purity in the starting material and the ability to add controlled amounts of impurities became prime research goals for the industry. Solving these twin problems involved both theoretical and empirical research.

Semiconductor materials research shows the importance of diversity in technical and scientific activities. The wartime alliance of commercial firms, academic laboratories, and government enterprises continued to perform semiconductor materials research. Industrial labs at BTL, DuPont, Texas Instruments, General Electric, Sylvania, RCA, and others, all active in wartime semiconductor-related research, either began or increased semiconductor research programs following the transistor discovery.[36] Government labs participated as well. The National Bureau of Standards, for example, carried out important semiconductor research explicitly in the interest of industry.[37]

The process of making electronics-grade germanium and silicon consisted largely of chemical reductions and purifications; thus, chemical firms led the research efforts. DuPont pursued research on silicon because of its potential as a substitute for titanium in pigments, one of its important businesses.[38] The company manufactured titanium dioxide using a chlorine reduction process. The need for purer silicon during the war suggested an analogous reaction using zinc and silicon chloride to DuPont researcher C. Marcus Olson.[39] The chlorine process allowed DuPont to supply military demand for silicon during the war and commercial demand afterward. Bell Telephone Laboratories (BTL) used DuPont silicon in transistor development work beginning in 1952, and industry demand expanded rapidly after 1954 when Texas Instruments announced the first mass-produced silicon transistor.[40] This device emerged from Texas Instruments' materials research program, run by BTL alumnus Gordon Teal.[41] By 1958 DuPont was making a thousand pounds of electronics-grade silicon per month.[42]

Bell Labs' diffusion process, a new way of making junction transistors announced in 1956, required purer starting materials than DuPont's chlorine process produced.[43] In the early 1950s Siemens, a large German electrical equipment firm, developed a process utilizing the decomposition of silane.[44] Westinghouse Electric bought the United States rights to this process and licensed it to DuPont, Merck, and other firms.[45] DuPont management had approved a 50,000-pound-per-year plant using its silicon chloride process in 1957,[46] but the new Siemens process and other refining techniques (discussed below) made DuPont's process technology increasingly obsolete. Backward integration at Texas Instruments and other semiconductor manufacturers further eroded the chemical firm's position, and DuPont left the business in the early 1960s when it decided not to integrate forward into electronic device production.

Silicon came to dominate as the base material for semiconductor devices. Though germanium remained widely used, the percentage of devices made from this material dropped steadily from 1954 to 1965.[47] Germanium supply firms such as Merck, Eagle-Picher, and Mallincrodt Chemical suffered from this change, though Merck at least picked up the slack with its own silicon program. More importantly, Siemens-process silicon, though purer than previously available, was still inadequate for new diffused devices.

The coupling between materials and devices must be appreciated as an important factor in the development of the industry. New device structure discoveries often motivated the search for new or better materials and processes, as in the case of the junction transistor, the MOS transistor, and later devices.[48] Put simply, the performance of a semiconductor electronic device depends on its structure, at both atomic and more tangible geometric levels. Controlling these features is thus absolutely fundamental. Starting with Bell Labs' transistor program in the 1940s, the art and science of making transistors depended on materials technology. This process involved "undertak[ing] to make suitable structures in solids by various techniques to fulfill the conditions in the device design."[49] William Shockley's 1949 theory of the junction transistor proposed that activity at the junction of differently doped semiconductor material (*p-n* junctions) would produce rectification and transistor action. Bell Labs instituted a research effort to produce such junctions. One year later two Bell Labs' researchers developed equipment in which they grew germanium of highly regular crystalline structure (called single crystals) and produced *p-n* and later *p-n-p* junctions.[50] Thus materials research made the new junction transistor possible.

This dynamic operated in both directions, however. For example, the success of the first junction devices triggered increased research into materials technologies to improve the performance and construction of such transistors. William G. Pfann at BTL originated zone melting (now more commonly known as zone refining), as a "new way of using the freezing process" to purify germanium.[51] This innovation, in Pfann's words, "combines the well-known fact that a freezing crystal differs in composition from its liquid, with the simple idea of passing a short molten zone along a lengthy charge of solid."[52] Since impurities are more strongly attracted to molten material, they "adhere" to it, and the moving molten zone carries them the length of the charge to the end. There the gathered impurities can be simply cut off. The process renders the remaining crystal extremely pure.

Though Pfann was modest in describing his discovery of zone melting, his central insight was far from "simple." The application of zone refining to semiconductor materials was highly useful, however, as commercial and experimental use quickly ensued. Demonstrating the "simple" applicability of Pfann's ingenious insight, firms and laboratories constructed zone refining equipment relatively easily from available information.[53]

Zone melting also proved useful for aligning the crystal's atomic structure, another requirement for improving transistor performance.[54] The existing standard procedure, the Czochralski method, adopted from a technique used earlier in the century for growing metallic crystals, first saw use for semiconductor crystals at Bell Labs in 1948.[55] By dipping a small piece of crystal which had the desired atomic structure into a pool of molten semiconductor material and then slowly withdrawing it, a worker could "pull" regular crystal rods out of the pool.

Despite working well for germanium, the Czochralski method proved inadequate for silicon because silicon's strong affinity for other materials caused its easy contamination by other substances with which it came into contact. When researchers tried pulling silicon single crystals from a molten pool, they found that introduced impurities from the container (the crucible) permeated the crystal and the process yielded less useful crystals. The search for solutions to this problem illustrates the participation of different institutions, and the importance of diversity, in materials technology innovation.

To address the contamination problem, researchers tried several strategies, including finding a crucible material with which silicon reacted less readily or simply eliminating the crucible. Both approaches involved materials technology research. More ambitious researchers attempted wholly different methods of producing silicon single crystals. Attacking the silicon dilemma took the combined efforts of semiconductor manufacturers, chemical firms, specialized materials firms, and private research laboratories, as the following episodes from the history of Shockley Semiconductor Laboratories, the earliest Silicon Valley semiconductor firm, show.

Shockley Semiconductor and the Refining of Silicon

After leaving Bell Labs in 1954, William Shockley formed his eponymous semiconductor laboratories in Palo Alto, California, in late 1955. Shockley intended to make a diffused silicon transistor, a device at that point monopolized by Texas Instruments. Gordon Moore, an early Shockley employee and later a founder of Fairchild Semiconductor Corporation, remembers that Shockley "had some ideas that he thought would give him [an] advantage." Prime among them was a new way to grow silicon crystals that Shockley thought would be a big improvement.[56] Shockley himself told of an "early days" project "to gamble on taking certain advanced steps in the growing of crystals," though his firm also had a "conventional growing program."[57] Shockley's lab pursued both crystal growing projects in cooperation with other research organizations.

In partnership with Stanford Research Institute, Shockley pursued different crucible materials: "We have been engaging in a cooperative program with Stanford Research Institute in connection with attempts to grow silicon carbide crystals from melts. In addition, we . . . have been supporting a program on new crucible materials for growing silicon crystals."[58] These new materials included graphite, silicon-coated graphite, silicon carbide, and silicon itself.

Graphite was used commonly for laboratory equipment but proved inadequate for holding molten silicon. On one hand, silicon reacted with the graphite surface to form a thin layer of silicon carbide which could provide protection against further contamination. On the other hand, small flaws in the graphite surface allowed the silicon to penetrate the crucible structure, where it formed silicon carbide. As this substance formed, it expanded and destroyed the crucible.[59] Neither efforts at using silicon carbide as the main material nor the silicon-coated graphite crucible project yielded useful results and Shockley halted the project in 1959.[60]

Using silicon as its own crucible, however, still looked promising to Shockley. The concept of using silicon as its own crucible was simple and brilliant. This "gamble on certain advanced steps" consisted of eliminating the crucible entirely, and, as Shockley described it, growing "silicon crystals from a puddle of molten silicon contained in a body of solid silicon."[61] However, selective heating of strictly defined areas of a solid silicon mass proved problematic and, despite valiant efforts, the crucible-less project folded under the pressure of other priorities.[62] In short, none of these projects yielded usable crucibles.

Shockley extended and received other offers for cooperative research in silicon crystal growth. In 1956 Battelle Memorial Institute proposed some cooperative work on single-crystal silicon. Shockley refused the offer but indicated that he would like to keep a channel open between the two organizations.[63] Two years later Shockley approached first the pharmaceutical firm Merck & Co. and, later, W.R. Grace Company, relatively new to the chemical industry, concerning a silicon crystal growing project.[64] In both cases Shockley proposed that his lab undertake the theoretical and planning aspects while development work would be done by the other organization. Concerning this project, Shockley explained:

> My thought is that the work would be supported largely by Grace personnel, who would carry out the work and arrange for the building of apparatus. Our participation would include the original planning of the program by myself, the evaluation of materials resulting from experiments at our laboratory and the obtaining of Government backing for the program if it were felt that Government support was desired.[65]

Shockley clearly perceived that the two firms' skills differed and the complementary nature of their diverse skill sets.

Non-reactive crucibles remained elusive and, ultimately, elaborations of Pfann's zone refining made the search unnecessary. H.C. Theuerer of Bell Labs altered conventional zone refining equipment to eliminate contact between the semiconductor material and any container. Moving the molten zone along a vertically suspended silicon crystal made both refining and single crystal growth possible. Surface tension held the molten zone in place.[66] Bell Labs' first application of this new technique produced refined single silicon crystals. Like simple zone refining, floating zone refining spread rapidly in the industry. By 1961, according to a Merck researcher, "float zone refining, once considered a hopeless commercial process," had "become practical."[67] The introduction of this technique made device grade silicon much more readily available.[68]

By the early 1960s, semiconductor materials refining technology had stabilized but the structure of industry supply had changed markedly. As silicon processing became less chemical and more mechanical/physical the special skills of chemical firms became less relevant. Firms such as DuPont, Merck, and Monsanto eventually withdrew from the business. At the same time, semiconductor firms like Texas

Instruments and Fairchild, among several others, integrated vertically into material production and the sale of device-grade silicon. Vertical integration rested on the skills accumulated by semiconductor firms in the course of their materials R&D, skills acquired through the actions of complementary diversity.

By the early 1960s the rapid technological shifts in semiconductor device design and production processes began to abate. Silicon devices made by oxide masking and diffusion techniques became dominant. Texas Instruments, the innovator of the silicon transistor, and Fairchild Semiconductor, whose oxide processing techniques became central to device manufacturing, led the industry in innovations and market power. Their vertical integration into semiconductor materials increased their dominance and ensured them a steady supply of high-quality materials. The development of crystal-growing and refining technologies made vertical integration possible, freeing the leading firms from reliance on the skills and resources of outside firms.

Crystal-growing, however well-developed by 1960, presented other problems. Slicing the crystals into the wafers on which to manufacture transistors, and polishing the wafers to sufficient smoothness incurred waste frequently approaching fifty percent of the original crystal. Prodded by such problems, firms and their researchers sought other means of preparing semiconductor wafers.

One such method was so-called dendritic crystal growth, by which semiconductor material was drawn from the melt in long, thin, "ribbons" of pure, single semiconductor materials rather than as round crystals.[69] As early as 1955 researchers at various labs undertook efforts in this area.[70] Device manufacturers such as Westinghouse, Sylvania Electrical Products, Texas Instruments, and Shockley Semiconductor Laboratories, as well as supplier firms such as Merck, Dow, and DuPont all conducted research of this type.[71]

Despite some success, dendritic materials encountered resistance within the semiconductor industry. The crystalline structure of the materials was inconsistent, and developments in other production processes accommodated round wafers only. Gordon Moore, head of Fairchild's R&D lab from 1958 to 1968, recalled:

> Dendritic silicon [was supposed to] replace the round roules. It was an interesting approach, but [other aspects of] the technology w[ere] developing around using round wafers . . . and [dendritic growth] was not completely successful in growing high quality material. Even when people were trying to use it, they were taking a cookie cutter and cutting round wafers out of the flat sheets so they could use the technology that was developing for spinning on photoresist.[72]

Dendritic growth programs, in other words, did not complement research developments in other process areas, and withered as a result.[73]

Semiconductor materials technology, then, advanced through several stages in the industry's first decades. In the earliest phase, in the 1940s and very early 1950s, universities and some commercial firms advanced knowledge concerning the composition, manipulation, and production of pure forms of germanium and silicon. With the commercial production of transistors and other semiconductor devices beginning in the early 1950s, more firms and laboratories began researching these materials, and the main locus of knowledge production shifted towards industrial laboratories. Supplier firms as well as their customer semiconductor firms conducted materials research, sometimes in close cooperation. But by 1960 or so silane reduction and zone refining techniques had become the industry standard, and semiconductor firms became the largest semiconductor materials producers. The complementary diversity that marked the development of semiconductor materials became less necessary as the major problems of crystal growth and purity were solved. Other materials critical to the industry, however, displayed the same developmental dynamic: reliance on diversity.

Chemicals

Research and development in the chemical aspects of semiconductor device manufacturing involved efforts in both the semiconductor firms and the chemical supply firms. Here, too, semiconductor manufacturing firms and their supplier firms performed complementary research to solve the industry's problems. Device manufacturing firms, as a rule, researched new methods of using chemicals to produce the electronic structures needed for proper device performance. Meanwhile, chemical firms researched, produced, and supplied chemicals suitable for the manufacturers' purposes with these applications firmly in mind.[74]

Chemical processes dominated semiconductor device manufacturing. Materials used in production equipment and virtually every step of the production process involved chemical processes. Semiconductor technology's need for ultra-pure materials extended to the process chemicals and associated equipment. One study of the industry holds that "the production technology of the semiconductor industry is essentially the technology of materials," but that "the change in materials technology really occurred in the chemical rather than the semiconductor industry."[75] While this statement exaggerates the situation, it nonetheless highlights the degree to which developments in semiconductor manufacture depended on the existence of complementary research and manufacturing skills.

A 1964 survey of chemical use in the semiconductor industry observed that "new products for electronics manufacturers have resulted because the chemical industry has recognized a need and undertaken research programs to satisfy this need."[76] The application of either "novel approaches in chemical technology or improved techniques using existing processes" caused these process improvements.[77] These approaches and techniques included improvements in purity, chemical handling and packaging, and specialized technical services provided by chemical industry research efforts.[78] The complementary research and development efforts relating to chemicals are well illustrated in the case of photoresists, materials used in patterning masks and wafers.

Photoresists

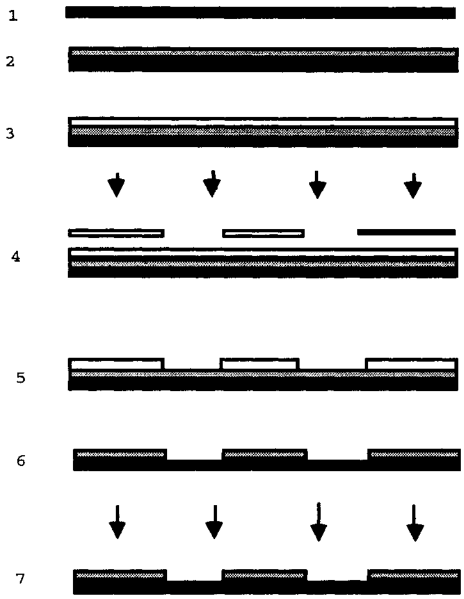
Virtually every production process in the early semiconductor industry can trace its origins to work done in government labs or under military sponsorship, and photoresist technology is no exception. The earliest large-scale application of photoresist technology to semiconductor device manufacturing took place at the Diamond Ordnance Fuze Laboratory (DOFL) in Washington, D.C. in the mid-1950s,[79] but the techniques quickly spread to industry as a part of the military program to upgrade the capabilities of the country's electronics industry.[80] Photoresist technology was crucial to Bell Labs' oxide masking and diffusion junction-making process. As such photoresists were central to the later success of the semiconductor industry.

Photoresists are chemicals that are affected by exposure to light, and can be used to place patterns on a flat surface.[81] The basic process was adapted from the printing and graphics industry, and came therefore to be called "photolithography."[82] The entire surface to be patterned, such as of a wafer of semiconductor material, is coated with photoresist, then a stencil, called a mask, is placed over it.[83] The wafer is then illuminated, and any unmasked areas are exposed. These exposed areas of photoresist harden, and the unexposed, unhardened areas are dissolved, leaving the desired pattern on the wafer.

In the oxide masking and diffusion process, a thin layer of oxide is formed on the surface of the semiconductor wafer (see Figure 1.) The photoresist is then applied over the oxide layer, masked, and exposed. Photoresist removal exposes certain portions of the oxide layer, which are themselves removed, revealing the underlying semiconductor surface. Dopants, the impurities which produce the desired electrical characteristics in semiconductor material, are then diffused into these exposed areas, changing their conductivity and creating semiconductor junctions, the basis for transistor action.

Adapting resist technology to microelectronics required many major and minor changes and innovations. Developing techniques for applying the resist smoothly, evenly, and quickly to the wafer surface was one area of research and development, but we will focus here on improvements in the qualities of the photoresist itself. Improvements in this case meant higher purity, correct

Figure 1:



1. The semiconductor wafer
2. An oxide layer is formed on the surface of the wafer
3. A thin layer of photoresist is applied on top of the oxide
4. The photoresist is exposed through a mask
5. After development, the exposed areas are dissolved, revealing selected areas of the oxide layer
6. Oxide layer is removed in selected areas, revealing selected portions of the semiconductor surface
7. Diffusion into the exposed areas (doping)

viscosity, and controlled size and distribution of particulate matter. These attributes of the photoresist affect the fineness and accuracy of patterns laid down on the wafer. Impure resists introduced unwanted elements into the process; variable viscosity produced uneven coverage of the surface and created inaccuracies in the pattern; irregular particulate size made it difficult to control the fineness of the pattern. Most research in this area was quite mundane, involving physical processes such as stirring, filtering, and diluting. Occasionally, however, scientifically intensive research was called for, and at such times the specialized expertise of the resist supplier became necessary.

Fairchild Semiconductor Company depended on photoresist technology from the start for patterning both masks and wafers. Gordon Moore recalls that the firm's founders were "intrigued with the idea of using photolithography in successive steps to make transistors."[84] To that end the firm hired James Nall from the DOFL, where he had originated the use of photoresist technology for transistor fabrication.[85] Working at first with Robert Noyce, one of Fairchild's founders, Nall took charge of the company's photoresist research.

The main supplier of resists to the industry was the Eastman Kodak Company, the largest and most advanced photographic company in the world. Kodak's research and development laboratory possessed long-standing expertise in photochemical technology, and Kodak was a major producer and purveyor of chemicals to various industries, notably the graphics industry. It was this involvement that motivated Kodak's research in resist technology.[86] From it's position as the major innovator in photochemical development, Kodak supplied technical assistance to its customers. When the electronics industry came into Kodak's circle, such technical services were extended to firms both individually and collectively.[87] Kodak sponsored seminars and colloquia that provided avenues for the dissemination of important information concerning resist technology.[88]

Resist technology became increasingly important at Fairchild with the introduction of monolithic integrated circuits in 1960. These devices contained in one piece of semiconductor material several elements such as transistors and diodes. Closely packed together, these elements nonetheless needed to be distinct from each other to function properly. Meeting these requirements demanded accurate masking operations to produce sufficiently fine patterns on the wafers. Complex mask-making, in the words of Gordon Moore, was "the heart of our technology."[89] Producing these increasingly fine patterns meant that Fairchild worked "right on the fringes of what people expected to do with [resists], so we were always finding the problems."[90] Solving those problems became crucial; resist operations were central to producing the required patterns on both masks and wafers.

Beginning in July 1960, FSC's resist research operations focused on improving cleanliness. The company installed positive pressure ventilation hoods which aided greatly in this effort, and, more importantly, the lab's Micrologic Section initiated a search for a resist solvent that could strip KPR (Kodak Photo Resist, the most commonly used resist) with less resort to scrubbing than the existing method. Experimenting with two commercially available strippers and two home brews, FSC researchers noted some improvement but found no magic formula. Elevating the temperature of the solvent bath increased the rate of stripping and reduced the need for agitation, but the heated solvents were hazardous and undesirably attacked other parts of the wafers.[91] A monthly report indicated that other parts of the lab were attacking the stripping problem differently: "Solvent stripping will be compared with removal by pyrolysis or burning, which is now being investigated by others."[92] Researchers also experimented with other commercially available strippers and various techniques. They attempted stripping with ultrasonic agitation (ineffective), high speed nitrogen jets (effective but unruly), and swabbing with cotton balls (effective, but harmful to the wafers).[93] Chromic acid, researchers found, worked admirably, but it sometimes left an undesirable stain on the wafer surface.[94]

By the end of 1960 the "chief obstacles" to improved resist operation included "scratching and marring of the glass masks and KPR coated wafers, mask imperfections, dirt and resulting holes in the KPR coating, uneven coating of the KPR, lifting of the KPR during etching, [and] inadequate definition of and variation in the size of the etched patterns...."[95] Some of these problems simply involved dirt, a consistent bane of semiconductor manufacture. Such problems were eventually solved by clean room technology and other measures. Some problems, however, involved the resist itself and required intensive analysis. Eastman Kodak worked closely with FSC to address these problems.

Fairchild and Kodak research projects at times duplicated each other. For example, production problems in 1961 spurred Fairchild's research on the thickness and evenness of resist layers. Defects in masks and wafers, particularly so-called "pinholes" in the resist layer, reduced the production yield of usable devices. The Mountain View production facility and the Palo Alto R&D lab reported differences in pinhole frequency, despite using similar processes to apply the resist. Ultimately the variance was traced to differences in the acceleration of the spinner used in applying the coating.[96] Arthur Engvall, in charge of the lab section's photoresist research, reported, "As a result of this finding the writer has begun a more extensive study of the effect of KPR thickness on pinholes and definition."[97] Initial findings confirmed that thicker resist layers would reduce pinholes. Thicker coatings, however, reduced the attainable pattern definition and so could not be used for finer pattern features.[98]

In this instance the Fairchild researchers took advantage of Kodak's complementary knowledge. Engvall and two other FSC researchers attended a Kodak-sponsored Symposium on KPR Technology in October of 1961. The meeting offered "very complete" resist research results which "for the most part confirmed [Fairchild's] recent findings and current thinking" concerning resist technology.[99] Kodak research supported Fairchild's dirt-reduction endeavor with the ventilation hoods; this approach was simpler and surer than keeping entire rooms dust-free. Likewise Kodak endorsed spinner application and filtering of KPR, both of which Fairchild had been doing.[100] Thus, Kodak's expertise added legitimacy to Fairchild's own efforts.

Not all Kodak research, of course, duplicated Fairchild's, and the FSC researchers obtained "most interesting and valuable information" on resist development at the October 1961 symposium.[101] Kodak had discovered that its previously recommended solvent, trichloroethylene, was too active to produce clean patterns. Instead, Kodak presented a new development method which showed great improvements in definition even with thicker resist coatings. "In view of these advantages," Engvall wrote, "we intend to adopt [the new method] for all R&D work" as well as recommend it for production after some testing.[102] Kodak's specialized expertise thus complemented Fairchild's, and process improvements stemmed from the combined efforts of the two firms.[103]

Kodak's new development procedure did not, however, cure all of Fairchild's photoresist difficulties. Early in 1962, the mask-making operation suffered from a KPR scum problem.[104] A residual film resistant to removal remained after development of the resist pattern. Kodak Metal Etch Resist (KMER), a newly developed formula, also produced a scum layer. Further applications of solvents produced problems with pinholes and lifting of the resist layer, exacerbating the difficulties with this process. Engvall and his crew set about to discover the nature of the scum layer as well as potential solutions. Possible causes of the scum included inherent qualities of the resist and some mechanism involving an interaction between the wafer surface and the resist.[105]

After two months' of trying different solutions, Fairchild approached Kodak in the late spring of 1962 for help with the scum problem.[106] Unfortunately, Kodak was of little apparent help at this point. Of a Kodak Resist seminar in San Francisco Fairchild attendees reported "nothing really new was presented," and the scum problem persisted.[107] Oddly, the problem was intermittent with no immediately apparent pattern of occurrence.

In 1963, however, Fairchild researchers serendipitously noticed a high positive correlation between the occurrence of scum and the local smog index.[108] Pursuing this line of inquiry they soon discovered that ozone, one of smog's main ingredients, caused the scum problem. The temporary solution was to concentrate resist work at low smog times, primarily at night. The longer term solution involved controlling the lab atmosphere to reduce ozone infiltration.[109]

Fairchild's solution of the scum problem, however, revealed the limits of information flow within the semiconductor industry. Fairchild did not reveal its discovery at the next Kodak photoresist seminar despite the fact that talks at the seminar revealed scum to be "one of the most troublesome problems some of our competitors have in photoresist work."[110] Considering the competitive value of the ozone discovery, Fairchild "did not volunteer any information."[111] In this case, the industry's habit of relatively free information exchange succumbed to purely business considerations.

The same conference, however, brought bad news to Fairchild: Kodak introduced a new thin resist, KTFR (Kodak Thin Filtered Resist) that looked like a "loss of competitive advantage on Fairchild's part, since we have had essentially this product available for some time through the use of our new filtering system."[112] The complementary, cooperative research dynamic in this instance worked against Fairchild's interests, though the impact in the end seems to have been small.

By early 1964, Fairchild's efforts in photoresist work seemed to have paid off. Work on scum repression, resist dispensing systems, spinner design, wafer rack design, exposure parameters, viscosity control equipment, pressurized and centrifugal filtering methods, and etching procedures had all achieved suitable solutions.[113] Lab management halted resist research, at least temporarily, but by November of that year constantly decreasing circuit element size demanded a re-examination of resist technologies. Resists remained a crucial part of device manufacturing. R&D management saw control of resist thickness as "the key to maximum resolution of all resist systems evaluated."[114] Kodak symposia summaries no longer appeared in the lab reports after the Fall of 1964, though mentions of visits to Kodak continued.[115] Whether this indicates that Fairchild people stopped going to the symposia is not clear. What is certain is that complementary research efforts marked resist research in a critical period of technology development. Kodak's expertise aided Fairchild in clearing the obstacles to producing the fine and precise patterns demanded in the fabrication of properly functioning and economically feasible devices.

Other Materials

Resist technology was not unique in requiring contribution from diverse and complementary sets of expertise. Materials that helped protect semiconductor devices from moisture, light, and other environmental factors which debilitated device performance were the subject of much research effort. These materials had to be prevented from interacting harmfully with the electrical functioning of the devices. In addition they had to be compatible with the other manufacturing steps; they needed to withstand a variety of operating conditions; and they had to remain intact and working for extended periods of time so as not to limit the inherently long lifetime of semiconductor devices. Semiconductor manufacturers looked to epoxy resins, other plastics, and glasses to provide protection. Standard materials of these sorts could not, as a rule, meet the stringent demands of semiconductor use, and as was the case with photoresists, their adaptation to new uses demanded complementary research efforts.

Again, work at Fairchild Semiconductor in the early 1960s illustrates this dynamic. Epoxy, plastic, and glass encapsulation promised considerable savings over alternative existing protective methods.[116] The heat needed to mold and harden many glasses and thermoplastics was high enough to damage the transistor. Epoxies, Fairchild researchers hoped, would relieve this problem. Gordon Moore recalled that the firm did "quite bit of work . . . on epoxy materials for encapsulation." The firm conducted this research "principally with other suppliers, but some internally."[117] The same was true of glasses and plastics, and Fairchild R&D Laboratory progress reports bear out this recollection.

In January 1960, for example, researchers from FSC R&D Laboratory's Chemistry Section had "discussions at Mellon Institute and Diamond Ordnance Fuze Labs," which "added to our technology" in, among other areas, epoxies.[118] FSC frequently transmitted its material evaluations to suppliers in the hopes that more suitable materials could be supplied.

Process chemicals supply another example of complementary research. Purity requirements for chemicals were substantially higher than for other industries. A 1964 survey of chemicals used in the semiconductor industry stated:

> The results of process improvements [by the chemical industry] have been especially noticeable in lowering the impurity content in the most commonly used acids, solvents and reagents. Initially most of these products were selected for the electronic user from regular production. As usage increased

> and the disadvantage of random contamination became evident, manufacturing and packaging processes were improved to produce ultra pure chemicals for the electronics industry. Today it is possible for a chemical to fail the specifications of the electronic user and still be pure enough to serve as an analytical reagent.[119]

Notwithstanding such progress in the chemical industry, Fairchild began in 1964 to make its own hydrochloric acid because commercially available grades remained too impure for its purpose.[120] The long-standing search for purity could not keep up with the increasing demands of the technology.

Conclusion

Advances in materials technology were fundamental to the semiconductor industry. With a couple of significant exceptions, progress in this area came from incremental accomplishments rather than bold leaps. Many of the materials and processes used by semiconductor manufacturers were adopted from other industries. Thus much of the materials technology research consisted of adaptation processes that by their nature are incremental. Another consequence of the adoption and adaptation process, however, lies precisely in the existence of a range of specialized skills built up in the donor industries. Such skills generally resided in materials suppliers, who had clear economic incentives to contribute to the adaptation process. Especially when suppliers had their own R&D labs, their contributions to semiconductor manufacturing were both complementary and significant.

From a pre-war base of research in industry and academia, semiconductor materials, mainly germanium and silicon, found wider electronics applications during the war. Producing semiconductors was in large part a chemical process, and chemical firms largely took charge of achieving the purity needed for electronic devices. Germanium, which was relatively easy to tame, benefited first from Bell Labs' zone refining process. Silicon, a more finicky material, resisted purity improvement until alterations in zone refining techniques produced device-grade material. This new technique, float zone refining, undercut the suppliers' position of chemical firms and soon allowed semiconductor firms to internalize the production of semiconductor materials. Their ability to do so, however, rested on the contributions made by suppliers' complementary research efforts.

The photoresist story also supports the importance of complementary efforts for advancing semiconductor technology. Initially, photoresist technology for device manufacture mirrored its earlier use in graphics. As semiconductor devices became more complex and demanding, resists needed to become more specialized as well. It was largely the combined efforts of semiconductor firms and suppliers, mainly Kodak, that enabled resist technology to meet the challenges of semiconductor applications. As with silicon, it appears that when semiconductor firms gained experience and competence in resists the supplier's role diminished.

Cooperation did not always, however, lead to success. Shockley Semiconductor Laboratories' crystal growing efforts with Stanford Research Institute and other firms failed. Likewise, dendritic growth projects saw little long-term success. In both instances, combinations of insufficient effort, lack of focus, and incompatibility with predominant industry trends contributed to the failure. These avenues would probably have remained unexplored, however, in the absence of cooperative efforts among complementary sets of expertise.

From the earliest wartime research endeavors involving many commercial firms and university laboratories to the later advances that led to workable, reliable, and efficient production techniques and processes, the semiconductor industry utilized the diversity of complementary sets of research and technical skills. The cases outlined in this chapter are supported by the industry's experience with virtually all relevant materials development: process chemicals, metals, glasses, and various plastics. Materials technology in the semiconductor industry, then, was a collective endeavor, one that depended on cooperation between the owners of complementary sets of knowledge.

Though the examples of complementary diversity illustrated here are relatively straightforward, the link between diversity and technical advance is not limited to just this one dynamic. Differences in approach as to the solution of the same problem, or competitive diversity, provides another relationship between diversity and technical advance. Such diversity in approaches to technological innovation is particularly important in situations of high uncertainty, where the pursuit of multiple approaches to a given problem may increase the chances of finding a solution. However, intermediate results of diverse approaches may be equally important to the overall advance of a technology. Knowledge produced researching one approach may prove useful in later projects; this may be true even if the original project failed functionally or economically.[121] Diversity, then, is itself complex and may not always appear as coherent. Its relationship to technical advance differs across innovation area and type and probably across industries and technologies. But if variation and selective retention models of technological development have any power, historians and others must understand more deeply how diversity works to advance technologies and under what circumstances it might serve to retard technical change with the same enthusiasm with which they explore selection mechanisms.

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[2] Charles Weiner, "How the Transistor Emerged," *IEEE Spectrum* 10, no. 1 (1973): 32. The interaction was facilitated by a series of what Weiner calls "social inventions": fellowships, publications, and the "organization of more effective patterns of communication" between scientists in industrial laboratories and academic settings.

[3] See Paul Hoch, "The Development of the Band Theory of Solids, 1933–1960," in Lillian Hoddeson et al., eds., *Out of the Crystal Maze: Chapters From the History of Solid-State Physics* (New York: Oxford University Press, 1992), 182-235.

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4 "Transistor Lineage," *Proceedings of the IRE* (November 1952): 1284.

5 William Shockley, "The Invention of the Transistor: An Example of Creative Failure Methodology," National Bureau of Standards Special Publication 388 (1944). See also his Nobel Prize acceptance speech in *Nobel Lectures, Physics, 1942–1962* (Amsterdam: Elsevier, 1964), 313ff.

6 Jack S. Kilby, "Invention of the Integrated Circuit," *IEEE Transactions on Electron Devices* ED-23, no. 7 (July 1976): 654.

7 Ernest Braun, "Selected Topics from the History of Semiconductor Physics and Its Applications," in Hoddeson et al., eds., *Out of the Crystal Maze,* 474.

8 George Basalla, *The Evolution of Technology* (Cambridge: Cambridge University Press, 1988); Joel Mokyr, *The Lever of Riches* (New York: Oxford University Press, 1990). In both authors' models, variation in technology is a reflection of diversity. Basalla uses the two terms interchangeably (see, for example, p. 2). Among others utilizing or arguing for evolutionary theories are James Cortada, *The Computer in the United States: From Laboratory to Market, 1930 to 1960* (Armonk, NY.: M.E. Sharpe, 1993) and Walter Vincenti, *What Engineers Know and How They Know It* (Baltimore: The Johns Hopkins University Press, 1990).

9 Richard R. Nelson and Sidney G. Winter, *An Evolutionary Theory of Economic Change*

(Cambridge, MA: Belknap Press, 1982). Nelson and Winter's theory, which relies on the understanding that economic change is fundamentally linked to technological change, has been expanded upon by Giovanni Dosi, *Technical Change and Industrial Transformation* (New York: St. Martin's Press, 1984). For a recent summation of work in non-biological evolutionary theory, see P. Paolo Saviotti and J. Stanley Metcalfe, eds., *Evolutionary Theories of Economic and Technological Change* (Chur, Switzerland: Harwood Academic Publishers, 1991).

[10] This is especially true of the adherents of the social construction of technology who, strictly speaking, are not evolutionary theorists but who nonetheless acknowledge their debt to evolutionary thought. In this theory, alternative, competing innovative technologies are selected for by user groups. The sources of the diverse alternatives are not mentioned; diversity is again simply assumed to exist. Neither does the idea of complementary innovations occur. See Wiebe Bijker, Thomas Hughes, and Trevor Pinch, eds., *The Social Construction of Technological Systems* (Cambridge, MA: MIT Press, 1989).

[11] Innovation in this industry took place solely within the confines of corporate, academic, and military institutional structures. In this way, it fits well the Schumpeterian theory of technological innovation becoming less the domain of talented individuals able to function outside of institutions and more the result of efforts of institutions able to engage the vast

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resources—both financial and human—demanded by increasingly complex technologies. Joseph Schumpeter, *Capitalism, Socialism, and Democracy* (New York: Harper, 1942). Certainly organizational economists acknowledge that firms differ, but little concrete work has been done in this discipline exploring the relationship between such differences and either economic or technological change. Wesley Cohen "Empirical Studies of Innovative Activity," in Paul Stoneman, ed., *Handbook of the Economics of Innovation and Technical Change* (Oxford: Blackwell, 1995), 182-264, gives an excellent overview and analysis of much of the relevant literature in this field. See also Kenneth J. Arrow, *The Limits of Organization* (New York: W.W. Norton & Co., 1974) and Richard Nelson, "Why Firms Differ, and How Does It Matter?" *Strategic Management Journal* 12 (1991), 61-74. Nascent economic investigations into the relationship between technical advance and inter-firm differences include Wesley M. Cohen and Steven Klepper, "The Tradeoff Between Firm Size and Diversity in the Pursuit of Technological Progress," *Small Business Economics* 4 (1992): 1-14; and idem, "Firm Size and the Nature of Innovation within Industries: The Case of Process and Product R&D," *Review of Economics and Statistics* (1994).

[12] Though "material," as in the phrase "material science" usually refers to metallic and ceramic solids or plastics, here it is used in a more general way to mean any substance out of which an artifact can be made, thus including chemicals.

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[13] Richard L. Petritz, "Contributions of Materials Technology to Semiconductor Devices," *Proceedings of the IRE* 50 (1962): 1025-1038.

[14] Petritz, "Contributions of Material Technology," 1025-1038.

[15] Petritz' article, however, focuses mainly on research in semiconductor materials and mentions the other materials only in passing. Petritz worked at Texas Instruments' Semiconductor Research Laboratory and went on, in the late 1960s, to co-found Mostek, one of the few spin-offs from TI, and a great, if brief, success.

[16] Eric von Hippel, *The Sources of Innovation* (New York: Oxford University Press, 1988) finds that many innovations come from users rather than suppliers.

[17] Ernest Braun and Stuart MacDonald, *Revolution in Miniature: The History and Impact of Semiconductor Electronics,* 2nd ed. (Cambridge: Cambridge University Press, 1978), 45-53; F.M. Smits, ed., *A History of Engineering and Science in the Bell System: Electronics Technology* (Murray Hill, NJ.: AT&T Bell Laboratories, 1985); Lillian Hoddeson, "The Discovery of the Point-contact Transistor," *Historical Studies in the Physical Sciences*, 12, no. 1 (1981): 41-76.

[18] Bell Labs maintained close relationships with other industrial and university laboratories. See Smits, ed., *Electronics Technology*, 29-30.

[19] Indeed, the cumulative nature of the growth of scientific knowledge depends on such communications. Much

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interesting material has been published on the form, extent, and consequences of scientific communication. Thomas Kuhn, *The Structure of Scientific Revolutions* (Chicago: University of Chicago Press, 1962) views such communication as essential to the growth of scientific knowledge. See also Diana Crane, *Invisible Colleges: Diffusion of Knowledge in Scientific Communities* (Chicago: University of Chicago Press, 1972). Edward Constant, *The Origins of the Turbojet Revolution* (Baltimore: The Johns Hopkins University Press, 1980) applies the Kuhnian notion of communities of practitioners to the development of technology, as does Vincenti, *What Engineers Know and How They Know It.* Several interesting articles on the subject can be found in Carnot E. Nelson and Donald K. Pollock, eds., *Communication Among Scientists and Engineers* (Lexington, Mass.: Heath Lexington Books, 1970). Robert Merton, "Priorities in Scientific Discovery: A Chapter in the Sociology of Science," *American Sociological Review* 22 (1957): 635-659 outlines some of the underlying social and professional meanings and purposes of the wide and free exchange of information among scientists.

[20] Bell Telephone Laboratories' early 1950s dissemination of information concerning the transistor, though in part motivated by a still-pending anti-trust suit, stands as a prime example in the semiconductor industry. Certainly BTL did not always distribute the information for free, but the fees charged were low considering the information's potential value. Adding to the general

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tendency toward free distribution of information among participants in the semiconductor industry was the relatively small size of the early community of practitioners and the ties established among the members through common educational and work experiences. See Smits, ed., *Electronics Technology*, xi-xii, 29-30.

[21] The intra- and inter-disciplinary exchanges of scientific and technical information were supplemented by deliberate efforts by various military and other governmental agencies to disseminate technical and scientific information among defense contractors and industrial sectors. See Daniel Holbrook, "Government Support of the Semiconductor Industry: Diverse Approaches and Information Flows," *Business and Economic History* 24, no. 2 (Winter 1995): 133-166.

[22] In other words, the simple existence of complexity in a new technology may not call into existence diverse efforts, but advances in that technology may depend on the prior existence of diverse techniques and processes in multiple technical and scientific areas.

[23] The search criteria were as follows: I compiled a starting list of semiconductor firms from various secondary sources. Supplementing this list were firms listed in the subject index under the headings "semiconductors," "electronics," "transistors," and "miniaturization." The 1965 volume had no subject index, so I went through the volume serially.

[24] It should be noted that no claim is being made here that these listings represent the total number of firms

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performing materials research relevant to electronics. Included here are only the firms listed in the *Industrial Research Laboratories* volumes which specifically claimed to be doing research in both materials and other areas of electronics. Absent from this list therefore are firms that supplied the industry but did not also perform research in electronics per se. Data in these volumes are mostly self-reported and may therefore not be complete. There is little doubt, however, that the data reflect the research orientation of the firms even if they are not a complete listing of the firms' activities.

[25] Shockley Semiconductor Laboratory's name was changed in 1958 to Shockley Transistor Corporation.

[26] Though Fairchild may not be typical of firms in the industry during the late 1950s and early 1960s, its atypicality lies mostly in its success, in contrast to the failure of so many other firms during this period. Additionally, Fairchild is one of only few semiconductor manufacturers from this period for which extensive and detailed records are available. These documents are mostly monthly progress reports from the firm's R&D laboratory, and reveal the particulars of Fairchild's research program. Intended for internal use only, these reports are more revealing than documents intended for public consumption.

[27] William O. Baker, "Advances in Materials Research and Development," in Peter A. Psaras and H. Dale Langford, eds., *Advancing Materials Research* (Washington, D.C.: National Academy Press, 1987): 3-24; National Academy of Science, *A Report by the*

Committee on Materials Relating to Long-range Scientific and Technical Trends of Interest to the Air Force (Washington, D.C.: NAS, 1957); *More Effective Organization and Administration of Materials Research and Development for National Security* National Research Council Publication 718 (1960).

[28] Spencer Weart, "The Solid Community," in Hoddeson et al, eds., *Out of the Crystal Maze,* 617-669.

[29] Weart, "The Solid Community," 657.

[30] See, for example, Weart, "The Solid Community"; Daniel J. Kevles, *The Physicists: The History of a Scientific Community in Modern America* (New York: Alfred A. Knopf, 1978); Sylvan Schweber, "The Empiricist Temper Regnant: Theoretical Physics in the United States, 1920–1950," *Historical Studies in the Physical and Biological Sciences* 17, no. 1 (1986): 55-98; Lillian Hoddeson, "The Roots of Solid State Research at Bell Labs," *Physics Today* 30, no. 3, (March 1977): 23-30; Lillian Hoddeson, "The Entry of the Quantum Theory of Solids into the Bell Telephone Laboratories, 1925–40: A Case Study of the Industrial Application of Fundamental Science," *Minerva* 18 (1980): 422-447.

[31] The somewhat artificial distinction between basic and applied research is especially blurred in the case of materials science. Laboratory techniques and procedures may look very much alike regardless of the researchers' final aims.

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[32] For the pre-war history of semiconductor materials research, see G.L. Pearson and W.H. Brattain, "History of Semiconductor Research," *Proceedings of the IRE* 43 (December 1955): 1794-1806; see also Hoddeson, "The Discovery of the Point-contact Transistor."

[33] C. Marcus Olson, "The Pure Stuff," *American Heritage of Invention and Technology* (Spring/Summer 1988): 58-63. Frederick Seitz was a paid consultant to DuPont and also worked for the Rad Lab radar development effort during the war, and thus could easily make the connection between DuPont's silicon capabilities and the needs of the radar project. Such consulting relations were not unusual among solid-state scientists, an indication of the tight multiple relationship between their disciplines and industrial research. See also David A. Hounshell and John K. Smith, *Science and Corporate Strategy: DuPont R&D, 1902–1980* (Cambridge: Cambridge University Press, 1988), 516.

[34] Ernest Braun, "Selected Topics from the History of Semiconductor Physics." Braun gives an excellent outline of the connections between the Rad Lab and various industrial and academic laboratories. See especially pages 454-466.

[35] Olson, "The Pure Stuff." Also Hounshell and Smith, *Science and Corporate Strategy*, 516.

[36] Note that all these firms were active in supplying electronics materials and/or systems to the war effort. Texas Instruments, then known as Geophysical

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Services, Inc., supplied electronic instruments to the military during the war. Braun and MacDonald, *Revolution in Miniature*, 58-59.

[37] Stephen Kalos, "The Economic Impacts of Government Research and Procurement: The Semiconductor Experience" (Ph.D. diss., Yale University, 1983), 91-106.

[38] Hounshell and Smith, *Science and Corporate Strategy*, 516.

[39] Olson, "The Pure Stuff," 60.

[40] Hounshell and Smith, *Science and Corporate Strategy*, 516.

[41] Patrick Haggerty, "Objectives, Strategies and Tactics," in *Management Philosophies and Practices of Texas Instruments, Incorporated: Presentations by Patrick E. Haggerty* (Dallas: Texas Instruments, Inc., 1965): 45-59.

[42] Olson, "The Pure Stuff," 62.

[43] Diffusion was a means of doping the semiconductor material by heating and exposing it to a gaseous atmosphere of the desired impurity. This drives the dopant into the semiconductor material. Bell Labs held a symposium for its transistor licensees in 1956 outlining the theory and techniques of diffusion.

[44] See Braun, "Semiconductor Physics and Its Applications," 477-478. Siemens' work in silicon production show the importance of diversity as well: its

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work was performed in cooperation with the Institute for Inorganic Chemistry at the University of Munich.

[45] "Business Week Reports on: Semiconductors," *Business Week* 26 March 1960, 74-121. Little information exists in the secondary literature on the entry of Merck or other firms into the semiconductor materials field. Firms such as Merck and Monsanto supplies process chemicals to the electronics industry, and may simply have sought to expand their activities related to semiconductor electronics. Dan J. Forrestal, *Faith, Hope and $5000: The Story of Monsanto* (New York: Simon and Schuster, 1977) merely mentions that the firm started making and supplying semiconductor materials, without further detail; *Values and Visions: A Merck Century* (Rahway, NJ.: Merck & Co., 1991) sheds equally little light on the details of that firm's entry into the semiconductor materials business.

[46] Hounshell and Smith, *Science and Corporate Strategy*, 516.

[47] Braun and MacDonald, *Revolution in Miniature*, 78. In 1957 germanium transistors accounted for 96% of all transistors. By 1965 this proportion fell to 54%. In this same year, however, silicon transistors represented almost 59% of the sales dollars.

[48] Braun and MacDonald, *Revolution in Miniature*, 54-87.

[49] Petritz, "Contributions of Materials Technology," 1025.

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[50] G.K. Teal, M. Sparks, and E. Buehler, "Growth of Germanium Single Crystals Containing *p-n* Junctions," *Physical Review* 28 (February 1951): 637-651; W. Shockley, M. Sparks, and G.K. Teal, "*p-n* Junction Transistors," *Physical Review* 83 (July 1951): 151-162.

[51] William G. Pfann, *Zone Melting* (New York: John Wiley and Sons, 1958), vii.

[52] Pfann, *Zone Melting*, vii.

[53] Pfann's book, in fact, was specifically intended to convey "all the information that a student, scientist, engineer, or manufacturer will need to plan a zone-melting process." Pfann, *Zone Melting*, viii.

[54] Pfann, *Zone Melting*, 153-170.

[55] Smits, ed., *Electronics Technology*, 20.

[56] Gordon Moore, interview with author, 21 February 1994.

[57] Letter, 7 March 1957, from Shockley to Dr. Benjamin Lax, Lincoln Lab, Shockley Papers, Stanford Special Collections, SA 90-117, Box 15, Folder "MIT 1957."

[58] Letter, 17 February 1958, from Shockley to Laboratory Procurement Office, US Army Signal Supply Agency, SA 90-117, 13/7.

[59] See Ray C. Ellis, Jr., "A Method For the Preparation of Semiconductor Grade Silicon," *Semiconductor Products* (August 1960): 36-38.

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[60] Memo, 15 January 1959, "1959 Research and Development Program," SA 90-117 13/5.

[61] Letter, 17 February 1958, from Shockley to Laboratory Procurement Office, US Army Signal Supply Agency, SA 90-117, 13/7.

[62] Letter, 17 February 1958, from Shockley to Laboratory Procurement Office, US Army Signal Supply Agency. Shockley explained: "This work has been abandoned currently due to the press of more urgent development work; however, we would be glad to reactivate the program if suitable contract support were available."

[63] Letter, 20 April 1956, from C.S. Peet, Battelle Memorial Institute, to Shockley, SA 90-117, 13/7.

[64] Letter, 22 May 1958, from Shockley to Robert T. Haslam, W.R. Grace, SA 90-117, 13/7.

[65] Letter, 22 July 1958, from Shockley to F.J. Sergeys, VP Grace R&D Div., SA 90-117, 13/8.

[66] Pfann, *Zone Melting*, 89-97.

[67] Frank Bourassa, "Vacuum Float Zone Refining of Silicon," *Semiconductor Products* 4, no. 4 (April 1961): 37.

[68] Growing and refining semiconductor materials required new and specially designed equipment, and most firms designed and made their own since none was commercially available. For example Shockley searched for workers with experience in making equipment as he was staffing his firm in 1956. As Shockley wrote, he was "interested in finding

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individuals who have been particularly inventive in making production machin[ery]." Letter, Sept. 13 1956, from Shockley to Barrett and Barrett, NY. Law Firm, SA 90-117, 13/12. Two years later the founders of Fairchild also needed such expertise in their venture. As Gordon Moore recalled, "essentially at that time we were the only guys in the business; we had to make a lot of our initial equipment." Gordon Moore interview with author 21 February 1994. This pattern was very common in the semiconductor industry and continued well into the 1960s. See Eric von Hippel, *The Sources of Innovation*, which uses semiconductor production equipment as an example of user-driven technological innovation. See also Walter Yorsz, "A Study of the Innovative Process in the Semiconductor Industry" (master's thesis, Sloan School of Management, MIT, 1976).

[69] The technique drew dendrites, thin crystals branching from a seed, from the melt. A film or web of the semiconductor material would simultaneously form between the dendrites. Another method drew the forming single crystal through a narrow slot as it solidified, thereby forming thin sheets of single crystal material. See J.A. Leonard and E.J. Patzner, "A Survey of Crystal-Growing Processes and Equipment," *Semiconductor Products and Solid State Technology* 9, no. 8 (1966): 35-42, especially the pictures on page 41.

[70] E. Billing and P.J. Holmes, *Acta. Cryst.* (1955), 8, 353.

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[71] See, for example, "New Developments," *Semiconductor Products* 2, no. 9 (1959): 59, an announcement that Westinghouse had "constructed long ribbons of semiconductor . . . crystals of germanium." Also the illustration, p. 21, in C.G. Currin and Elmo Earleywine, "Advances in Elemental Semiconductors," *Semiconductor Products and Solid State Technology* 7, no. 6 (1964): 20-25.

[72] Moore, interview, 29 June 1994.

[73] Additionally, despite their importance in the proper functioning of semiconductor devices, materials made up only a small portion of total manufacturing costs, reducing the economic incentives for innovations in new forms of crystals. See Edward Keonjian, ed., *Microelectronics: Theory, Design, and Fabrication* (New York: McGraw-Hill Book Co., 1963), especially pages 10-14, 347-356. Note also that as component size decreased, as in integrated circuits, materials cost per function decreased also.

[74] A 1964 survey lists some 300 firms supplying chemicals to the industry. The list of suppliers includes both the well-known chemical companies (DuPont, Merck, Dow, Union Carbide) and smaller, lesser known firms, such as Special Chemical Co., Topper Mfg. Co., etc. "Manufacturers' Directory of Passive Solid State Materials," *Semiconductor Products and Solid State Technology* 7, no. 7 (1964): 32-35.

[75] Jerome Kraus, "An Economic Study of the U.S. Semiconductor Industry" (Ph.D. diss., New School for Social Research, 1973), 201.

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[76] H.G Verner and W.B. Haynes, "The Uses of Chemicals in Solid State Device Fabrication," *Semiconductor Products and Solid State Technology* I, vol. 7, no. 7 (1964): 13-17. Quote on page 14.

[77] H.G Verner and W.B. Haynes, "The Uses of Chemicals," 13-14.

[78] Included in the survey are graphite used in fixtures, jigs, and containers; quartz used for the same and other purposes; Teflon, polyethylene, and polyvinyl chloride used for handling chemicals; water purification equipment and supplies; etchants; various gases; pure metals; desiccants; and improved packaging and handling materials and techniques that maintain chemical purity during transport and production. I do not mean here to diminish the importance of any of these; to cover all of them would simply be redundant.

[79] J.R. Nall and J.W. Lathrop, "The Use of Photolithographic Techniques in Transistor Fabrication," DOFL Technical Report TR-608 (1 June 1958).

[80] Norman J. Doctor, Quentin C. Kaiser, T.M. Liimatainen, and David Williams, "DOFL's Microminiaturization Activities, and Their Relation to Parallel Efforts," DOFL Report TM-61-41 (1 September 1961). This report states that the lab had been "called upon to guide private industry" in electronic miniaturization, and that "such guidance is considered to be one of [the lab's] proper functions." (3). Military preparedness policies included the transfer of techniques developed in military labs into industry.

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[81] More technically, photoresists are photosensitive organic materials. Negative photoresists form polymers upon exposure to light; positive photoresists are depolymerized by exposure to light.

[82] It is not, strictly speaking, photolithography, but rather is a specialized photographic printing process.

[83] The same basic technique is used to make the masks themselves, the main difference being that the resist-covered mask plate is exposed by image projection rather than through a mask.

[84] Gordon Moore, interview with author, 29 June 1994.

[85] Nall and Lathrop, "The Use of Photolithographic Techniques."

[86] The 1912 founding of Kodak's R&D lab is related in Reese V. Jenkins, *Images and Enterprise: Technology and the American Photographic Industry 1839 to 1925* (Baltimore: Johns Hopkins University Press, 1975), especially pages 300-318.

[87] Indeed, Nall and Lathrop thank Kodak for its help in the original DOFL program. Nall and Lathrop, "The Use of Photolithographic Techniques," 14.

[88] Kodak designed these meetings for specific industries, and held them periodically at different sites around the country. For example, Fairchild records (cited later herein) indicate attendance at seminars both at Kodak headquarters in Rochester and at regional seminars in San Francisco.

[89] Moore and Grinich, 8 March 1961, 5. SA 88-095, 6/2.

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[90] Moore interview, 29 June 1994.

[91] FSC Progress Report, Micrologic Section, 1 July 1960, 6-7. SA 88-095, 5/2.

[92] FSC Progress Report, Micrologic Section, 1 July 1960, 7

[93] FSC Progress Reports, Micrologic Section July, August, September 1960. SA 88-095, 5/2, 5/3.

[94] FSC Progress Report, Micrologic Section 1 November 1960, 9. SA 88-095, 5/4.

[95] FSC Progress Report, Micrologic Section 1 December 1960, 9. SA 88-095, 5/6.

[96] Resist coatings could be applied by several methods. In less exacting situations brushing or dipping could be used. Spraying improved layer uniformity, but spinning was better yet. The wafer was placed on a motorized turntable. Spinning distributed a small amount of resist applied to the wafer. Edge spinners positioned the wafers around the perimeter of the turntable; center spinners placed the wafer in the center.

[97] Microelectronics Research Section, 1 October 1961, 8. SA 88-095, 6/8.

[98] Thicker layers meant a greater chance of lateral undercutting during resist removal so that features were enlarged on the wafer surface. The increased time needed to etch through the thicker layers also increased the possibility of producing pinholes and other faults.

[99] Microelectronics Research Section, 1 November 1961, 7. SA 88-095, 6/9.

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[100] Microelectronics Research Section, 1 November 1961, 8. SA 88-095, 6/9.

[101] Microelectronics Research Section, 1 November 1961, 8.

[102] Microelectronics Research Section, 1 November 1961, 10. SA 88-095, 6/9.

[103] The same symposium also relayed information concerning new methods of making multiple images from one exposure. Upon testing in their own labs, however, FSC researchers found that "the images produced will not be sharp enough nor will the resolution be adequate for microelectronics." Microelectronics Research Section, 1 November 1961, 5. SA 88-095, 6/9.

[104] Microelectronics Research Section, Feb., 1 April 1962. SA 88-095, 7/3.

[105] Microelectronics Research Section, 1 March 1962, 8. SA 88-095, 7/2.

[106] Microelectronics Research Section, 1 May 1962, 7. SA 88-095, 7/3.

[107] Microelectronics Research Section, June 1962, 7. SA 88-095, 7/4.

[108] Microelectronics Research Section, 1 August 1963, 8. SA 88-095, 8/1.

[109] Microelectronics Research Section, 1 September 1963, 5. 88-095, 8/2.

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[110] Microelectronics Research Section, 1 June 1964, 5. SA 88-095, 10/2.

[111] Microelectronics Research Section, 1 June 1964, 5.

[112] Microelectronics Research Section, 1 June 1964, 6. SA 88-095, 10/2.

[113] Microelectronics Research Section, 1 April 1964, 4-7. SA 88-095, 9/3.

[114] Materials and Processes Section, 5 November 1964, 35. SA 88-095, 11/1. A 1964 reorganization of the R&D lab folded certain research areas, resist technology among them, into the Materials and Processes Section.

[115] For example in a Progress Report from the Transducer Section, 1 March 1965, 4. SA 88-095, 11/4.

[116] The most common technique up to the early 1950s was canning, sealing the device inside an all-metal, metal/glass, or metal/ceramic enclosure. This technique was directly adapted from tube-based electronics.

[117] Moore, interview, 29 June 1994. The main suppliers of epoxy to the electronics industry included Epoxy Products Co., 3M, DuPont, Dow Chemical, Permacel, Armstrong, Philadelphia Resins, M.A. Bruder & Co., Shell Chemical Corp., Emerson and Cummins, Furane Plastics, Hysol, Epoxylite, Norwich Plastics, Smooth-On, and Polymer Industries. "Industry Report: Materials and Machinery Used in the Semiconductor Industry," *Semiconductor Products* 4, no. 6 (June 1961): 45-47.

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[118] Chemistry Section Progress Report, 1 January 1960, 4. SA 88-095, 5/1.

[119] Verner and Haynes, "The Use of Chemicals," 14.

[120] Materials and Processes Section Progress Report, 1 May 1964, 31. SA 88-095, 10/1.

[121] For a brief analysis of this dynamic using the integration and miniaturization of electronic circuitry as an example, see Holbrook, "Government Support of the Semiconductor Industry." See also Walter Vincenti, "The Retractable Airplane Landing Gear and the Northrop "Anomaly": Variation-Selection and the Shaping of Technology," *Technology and Culture* 35, no. 1 (1994): 1-33, which urges historians of technology "cherchez la variation."