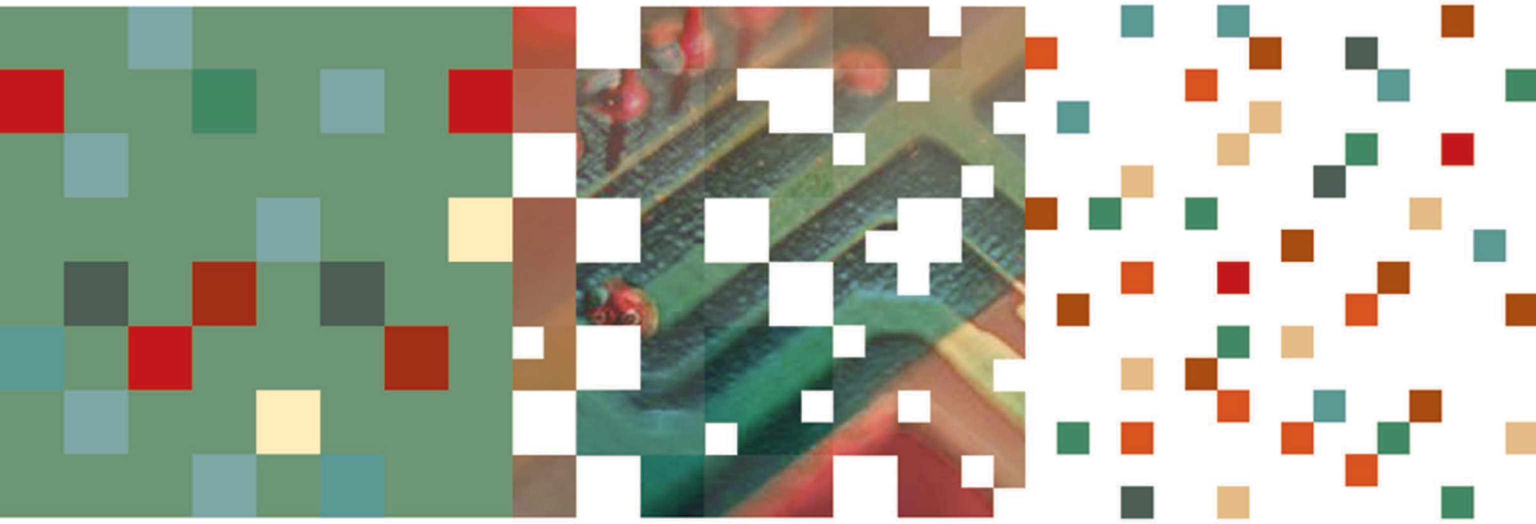
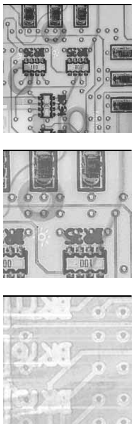
UNDERSTANDING MOORE'S LAW



Four Decades of Innovation

Edited by David C. Brock



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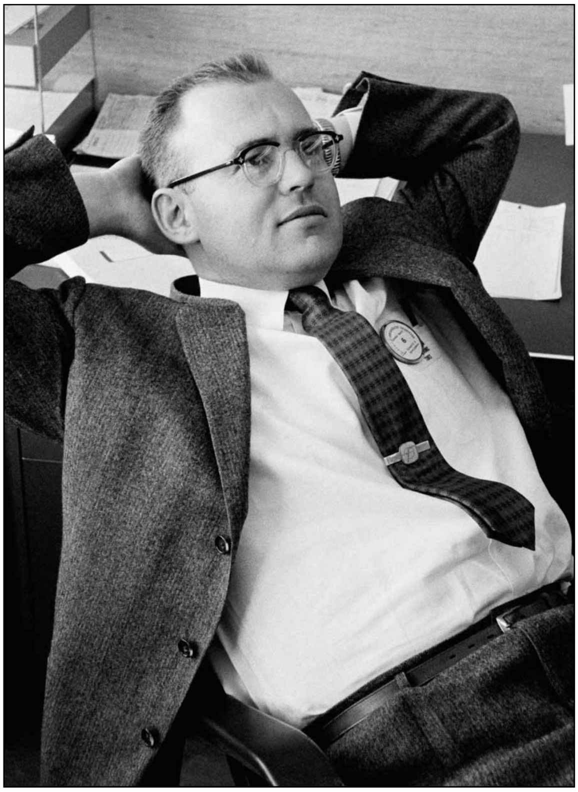

Gordon E. Moore in 1960.
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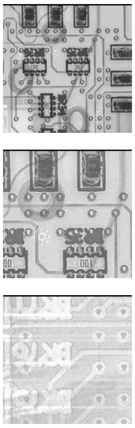

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Four Decades of Innovation

Edited by David C. Brock

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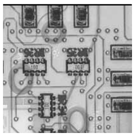
“Chymistry is the great field of knowledge for the extension of electrical knowledge . . . yet their relation to each other has been but little considered.”

— *Joseph Priestley,* 1766



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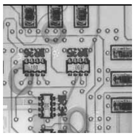
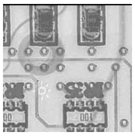




PREFACE

The rise of semiconductor electronics and its underlying manufacturing technology are among the most important developments of the past half-century. Integrated circuits—silicon chips—have transformed every area of economic, technological, and social activity. Insights into the dynamics that have brought us this silicon revolution are vital to our understanding of the world today and our common future.

For the past forty years, Moore's law has served as a unique guide to the dynamics of the silicon revolution. Originating as an observation and prediction about the economic and technical trends at play in the early years of integrated circuit technology, Moore's law eventually became an industry expectation. Later, it became the organizing goal of a multibillion-dollar global industry. Even more recently, with the proliferation of silicon chips into nearly every aspect of contemporary life, Moore's law serves as an emblem for the whole of technological change.

What is Moore's law? Where did it come from? What is the underlying technology for making silicon chips? How has it changed, and who did the work? Who is Gordon Moore? Where is Moore's law leading? This book aims to answer these questions for the general reader. Part One, Historical Introduction, places Gordon Moore and semiconductor electronics within a broad sweep of scientific and technological history. Arnold Thackray's review, "Before Moore's Law: Lineages of Chemistry and Electricity," emphasizes the longstanding and productive intersections of chemistry with electronics that form an important context for the silicon revolution. David C. Brock's essay, "The Backdrop to Moore's Law: Developments in Semiconductor Electronics to 1965," introduces semiconductor technology and Gordon Moore's involvement with it up to his formulation of Moore's law.

Part Two, Articulations, presents Gordon Moore's major statements of his eponymous law. The section begins with an introductory essay by Brock, "A Clear Voice: The Origins of Gordon Moore's 1965 Paper," which describes the immediate context in which Moore developed his first statement of Moore's law. Next, reproduced here for the first time, is Moore's original manuscript for his first publication of Moore's law. Reproductions of Moore's two major published articulations of Moore's law follow: his paper of 1965, "Cramming More Components Onto Integrated Circuits," and his published speech of 1975, "Progress in Digital Integrated Electronics." Here the reader can trace the evolution of the expression of Moore's law through the original manuscript, the first publication, and the tenth anniversary update. Part Two concludes with a new, important contribution by Moore, "Moore's Law at Forty," his fortieth anniversary update and reflection.

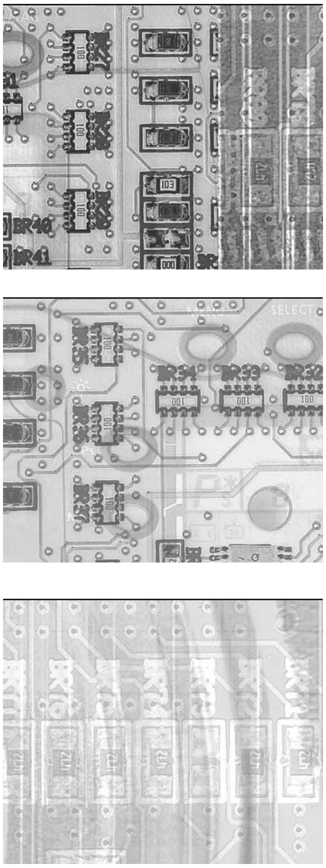
This book has its beginnings in a symposium held in the spring of 2005, Moore's Law at 40: Chemistry and the Electronics Revolution, at which Moore delivered his "Moore's Law at Forty" update. Organized by the Chemical Heritage Foundation, this symposium gathered key contributors to and commentators on the silicon revolution. Part Three of the book, Reflections, presents a review of their reflections and observations about Moore's law and its four-decade history, as well as their predictions for the future.

ACKNOWLEDGMENTS

This publication is the product of many minds. As a result, lengthy thanks are due to many. Nicola Twilley contributed greatly to the original conceptualization of our symposium and to its organization. Robert Lopata and others furthered these efforts and made our event a notable success. Christophe Lécuyer and Arthur Daemmrich served as long-suffering sounding boards and sources of ideas for the organization of this volume and its contents. Our gratitude extends to the CHF events and publication teams for the excellent hosting of our symposium and for the editing, design, and production of this volume. We are grateful to Susan Cronk for her transcriptions.

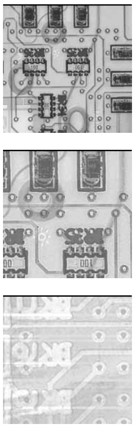
Our primary debt is owed to the speakers and moderators of our conference and to those individuals and organizations who promoted and sponsored it. For speaking at our symposium, we thank Gordon Moore, Rodney Brooks, Patrick Gelsinger, Raj Gupta, Carver Mead, Elsa Reichmanis, AnnaLee Saxenian, and Harry Sello. For their able services as moderators and commentators, we thank Dennis Hess, Rob McCord, and Miles Drake. Our special thanks go to Arnold Thackray, the president of CHF, for his many roles: speaker and moderator at the event, contributor to its intellectual and logistical organization, and active contributor to our explorations of the intersection between chemistry and electronics.

Our symposium was organized in association with the Electrochemical Society. In that connection, we thank Kathryn Bullock for her advice, assistance and enthusiasm. Similarly, Rob McCord did much to promote our symposium through the Eastern Technology Council. The symposium was made possible through the financial support of the Intel Corporation (Platinum Sponsor), the Rohm and Haas Company (Gold Sponsor), and our Silver Sponsors: Cabot Microelectronics Corporation, Degussa Corporation, Mallinckrodt Baker, Solid State Equipment Corporation, 3M Company, and Wacker Chemical Corporation. Lastly, we express our deep appreciation to John Haas for his long support of both CHF and our chemical history of electronics project.



PART ONE

HISTORICAL INTRODUCTION



CHAPTER 1

BEFORE MOORE'S LAW: LINEAGES OF CHEMISTRY AND ELECTRICITY

Arnold Thackray

Moore's law offers fundamental insight into the most transformative technology of the past half century: silicon semiconductor electronics. By reflecting on Moore's law and its contexts, we may gain a greater understanding of this technology and its effect on our lives. Why such a reflection should be offered by the Chemical Heritage Foundation (CHF) and developed through a symposium that took place in Philadelphia requires some explanation.

CHF's symposium was held in May 2005 to mark the fortieth anniversary of Gordon Moore's original publication of Moore's law in an article (reprinted in this primer and titled "Cramming More Components Onto Integrated Circuits"). May 2005 also coincided with the fiftieth anniversary of the event that brought the silicon to Silicon Valley: the establishment of the Shockley Semiconductor Laboratories. Why would CHF, an organization devoted to the history and heritage of the chemical sciences and technologies, undertake a symposium on the history of silicon electronics? Simply put, silicon semiconductor electronics is the most recent development in a centuries-old history of the interconnection between chemistry and electricity.

There is a strong lineage of important research centered on the electrical and chemical properties of materials and their interconnections, tracing back to at least the eighteenth century. Gordon Moore and his contemporaries who authored the silicon revolution are the most recent generation of researchers in this line. Indeed, silicon semiconductor electronics are created by the chemical and physical manipulation of silicon and other materials to produce desired electronic functionality. The silicon revolution is the most recent of several consequential episodes in the long engagement of the chemical with the electrical.

But why Philadelphia as the location for the symposium? What connections does this place have with the subject? CHF is located in Philadelphia because of the city's central role in the history of the chemical enterprise in America. The story stretches from the heyday of Benjamin Franklin's scientific fame to the heady era in the middle of the twentieth century that gave rise to silicon electronics.

Benjamin Franklin (1706–1790) and his electrical activities are famous. Franklin, of course, made the whole territory of electricity very much the subject of conversation and speculation, and Philadelphia was central to that community of inquiry. Among Franklin's scientific contributions was his discovery of Joseph Priestley, a young dissenting protestant minister in England, whom Franklin persuaded to venture into the new field of electrical investigations and thereby into a career as a scientific researcher. Priestley would go on to earn a reputation as one of history's greatest chemists and eventually emigrate to Franklin's Philadelphia and Pennsylvania.

Priestley (1733–1804) is a member of the second generation of our lineage, along with Luigi Galvani (1737–1798) and Alessandro Volta (1745–1827). Franklin's influence most directly reached this second generation through his relationship with Priestley. Indeed, Priestley's first scientific book was titled *History and Present State of Electricity* and included original experiments. In this book, Priestley delivers a remarkably prescient statement about the relationship between the science of chemistry and the science of electricity: "CHYMISTRY [is] the great field of knowledge for the extension of electrical knowledge: for chymistry and electricity are both conversant about the latent and less obvious properties of bodies; and yet their relation to each other has been but little considered." As we approach the 250th anniversary of this statement, one might say that Gordon Moore and his successors are bringing to fruition this relationship of chemistry and electricity.

The first great event in the sequence that followed Priestley's proclamation was Luigi Galvani's work with frogs' legs some twenty-five years later. Galvani, by connecting a strip made of iron and brass with each metal touching a frog's leg, made the leg twitch, even though the frog was obviously not alive. The observation prompted Galvani to posit an "animal electricity," a form of electrical fluid responsible for the activity of muscles.

As is usually the case in science, Galvani's claim was greeted with skepticism, particularly by his contemporary Allesandro Volta. Volta was convinced that Galvani's results had nothing to do with the inclusion of animal matter and everything to do with the two types of metal. Volta undertook a similar experiment connecting two dissimilar metals through a brine solution, leaving out the frogs' legs and thereby produced current electricity and the first battery.

With Volta's work a new world had been entered. Current electricity became a great sensation. Here was electricity produced by chemical means. An indication of how great a stir Volta's work caused is evidenced by Volta's personal summons to demonstrate the electric current phenomenon to Napoleon Bonaparte, who later made him a count.

For the next generation of researchers, Volta's results led to the emergence of a relatively "big science" approach to the exploration of the relationship of chemistry with electricity. Humphry Davy (1778–1829) grasped the true potential of what Volta had initiated. He had the insight that if one battery cell is good, then hundreds must be better. This enabled him to decompose chemical substances that had resisted earlier efforts, thereby discovering new chemical elements such as sodium and potassium.

Davy's discoveries caused a great sensation. The pace of discovery began to quicken. Davy, like Franklin, also contributed greatly to science by recognizing the research talents of a contemporary. In Davy's case, the individual was an impecunious young Michael Faraday (1791–1867), who first became Davy's assistant and eventually his scientific successor as professor of chemistry at the Royal Institution in London. By connecting electricity to magnetism, it was Faraday who would attain the next great milestone in our understanding of electricity. Moreover, Faraday built on Davy's work and codified the laws of electrolysis—the decomposition of chemical substances by electricity. In so doing, he introduced the most familiar terms of both electrochemistry and electronics: ion, electrode, cathode, and anode.

Faraday's electrical inventions would endure a lengthy delay before their practical application. His work in electrolysis was eventually deployed by the fourth generation in our lineage: the generation of two electrochemical entrepreneurs, Charles Hall and Herbert Dow. In the 1880s Charles M. Hall (1863–1914) developed a new electrolysis-based method for producing aluminum. Hall's commercial enterprise, the Pittsburgh Reduction Company, later renamed Alcoa, involved the large scale-up of electrolytic processes. Hall's operations soon moved to Niagara Falls to satisfy the operation's need for hydroelectric power. Chemistry and electricity were now connected on both the research and industrial fronts. Reflecting this connection, in 1902 the Electrochemical Society was established in what was by then the industrial and manufacturing city of Philadelphia.

Another example of the chemistry and electricity arena shifting from the laboratory to the industrial plant is Even's Mill. Herbert Dow (1866–1930), fresh out of the Case Institute of Technology, was at the leading edge of electrochemistry. He set up his industrial operation in a former flour mill, Even's Mill, where he successfully electrolyzed brine on a major scale to produce bromine—the much-in-demand essential ingredient in bromides, or tranquilizers. For their manufacture of this popular medicine, a Philadelphia firm that is today part of Merck placed Dow's first order for bromine. With this singular bromine order, the Dow Chemical Company was successfully launched, demonstrating yet another combination of chemistry and electricity.

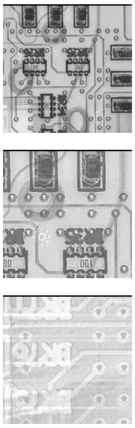
It is at this point that our story ratchets up to another level of complexity, as the word *electronics* is added to the mix. Developed across the first two decades of the twentieth century, it was the vacuum tube that would launch the age of electronics and guarantee the future of radio. In the mid-1930s Arnold O. Beckman (1900–2004), a young chemistry professor at Caltech, made a revolutionary combination of chemistry and electronics when he used the vacuum tube to create an effective pH meter.

Beckman's instrument used vacuum tube electronics to produce a direct measurement of a fundamental chemical property: pH. This revolutionary tool used electrical properties to transform the pace and character of chemical research itself and thereby opened the way for the development of a host of new instruments that employed electronics to yield major clues to the composition of complex chemicals. Electronics was crucial to the radical change in the power and pace of chemical research at mid-century.

Vacuum tube electronics enabled another more generally transformative development at mid-century: the creation of electronic digital computers. In these early years, however, these vacuum tube machines held more promise than practicality. With alarming regularity, one or another of the thousands of vacuum tubes required for a computer failed. The most daunting challenge for the machines' operators was how many minutes they would function before failed tubes closed the computer down.

At that very moment the answer to these computer operators' needs came from a new combination of chemistry and electricity. The whole world of electronics was about to take on a new shape. In 1947, through the work of William Shockley (1910–1989) and others at Bell Labs—less than 100 miles from Philadelphia—the first transistor was created, and semiconductor electronics was born. The essence of the discovery was that, by chemical and physical means, the class of materials called "semiconductors" could be precisely molded into devices with exacting electrical behaviors. The transistor fulfilled the function of the vacuum tube, but better. It was a robust solid with dramatically reduced size and increased reliability. In the last 1940s and early 1950s, electronics was centered on the East Coast, with firms like Philco, RCA, and IBM. Philadelphia was one natural locus of activity—whether as the home of the Solid State Circuitry conferences or as a center for hiring promising young engineers (for example, Robert Noyce, who went to Philco in 1953). However, this eastern and Philadelphia-linked dominance was not to last.

This rapid survey of the engagement of chemistry with electricity brings us to a fateful telephone call made just fifty years ago. That call would tie together the fates of Arnold Beckman and William Shockley, ignite the silicon electronics revolution, change the lives of the individuals who would deliver on the promise of this revolution, and lead to the creation of Silicon Valley. In 1955 Shockley, who had been an undergraduate student of Beckman's, called his professor, trading on their Caltech connection and Beckman's entrepreneurial reputation. Shockley was looking to leave Bell Labs to establish a company to produce a new wave of semiconductor electronics built from silicon. Beckman and Shockley, who had each made significant contributions to the intersection of chemistry with electronics, established the Shockley Semiconductor Laboratory as a wholly owned subsidiary of Beckman Instruments. Beckman Instruments was in Pasadena, California, but Shockley's mother lived—and hence Shockley Semiconductor Laboratory was located—in Palo Alto. Among the individuals who Shockley gathered for his new effort were Gordon Moore (1929–) and Robert Noyce (1927–1990). Moore and Noyce together would fulfill the promise of the silicon electronics revolution at the firms that they created after leaving Shockley's lab: Fairchild Semiconductor and Intel. By their genius and by extraordinary chemical and physical transformations of the major ingredient, silicon, the microprocessor was born—a significant development for society, culture, and the global economy, which is as profound as it is ongoing.



CHAPTER 2

THE BACKDROP TO MOORE'S LAW: DEVELOPMENTS IN SEMICONDUCTOR ELECTRONICS TO 1965

David C. Brock

At the close of the nineteenth century, physicists and chemists who were interested in a group of chemical elements and compounds known as "semiconductors" had identified a handful of remarkable properties that these materials possessed. As their name implies, the common boundary that researchers drew around these materials was determined by their electrical characteristics. Semiconductors stood in the middle ground between highly conductive metals and nonconducting insulators. While semiconductors were neither fish nor fowl when it came to conductivity, scientists had observed a set of intriguing electrical behaviors in the materials. They were unusual in that, unlike metals, their electrical resistivity failed to increase with rising temperatures. They appeared to violate other norms as well, in that they *rectified*. That is, unlike typical conductors, semiconductors had the ability to restrict the passage of electrical current to one direction and thus, to transform, or rectify, AC current into DC current. Moreover, scientists revealed that the electrical properties of semiconductors could be altered when exposed to light—changing their resistivity and even producing a current.[1]

In the opening decade of the twentieth century, scientists and engineers found that by placing a metal point-contact (colloquially known in the technical community as a "cat's whisker" for its resemblance to the same) on a crystalline mass of semiconductor material, they could form a practical rectifier for detecting radio signals.

These "crystal detectors" were important components during the development of radio technology in its early period. However, they were soon eclipsed by the advent of the vacuum tube. Scientists and engineers produced vacuum tubes that could perform the same rectifying function as the crystal detectors, as well as other tubes that could act as powerful electrical amplifiers. In the 1910s and 1920s the vacuum tube reigned supreme as the symbol of the new radio era and the dawn of the electronic age.[2]

While scientific and engineering attention predominantly focused on the theory and practice of vacuum tube technology in these early decades, the study and use of semiconductors lay relatively dormant. Interest in semiconductors began to reawaken, however, toward the end of the 1920s following the rise of the new physics of quantum mechanics and continued work by chemists to plumb the chemical properties of such semiconductor elements as silicon and germanium. By 1930 scientists—largely working in academic settings—had established a research program to understand the electrical behavior of both metals and semiconductors through the lens of the new quantum theory. In particular, a research community coalesced around the issue of understanding the roles of the surface and bulk of semiconductor materials in the process of rectification.[3]

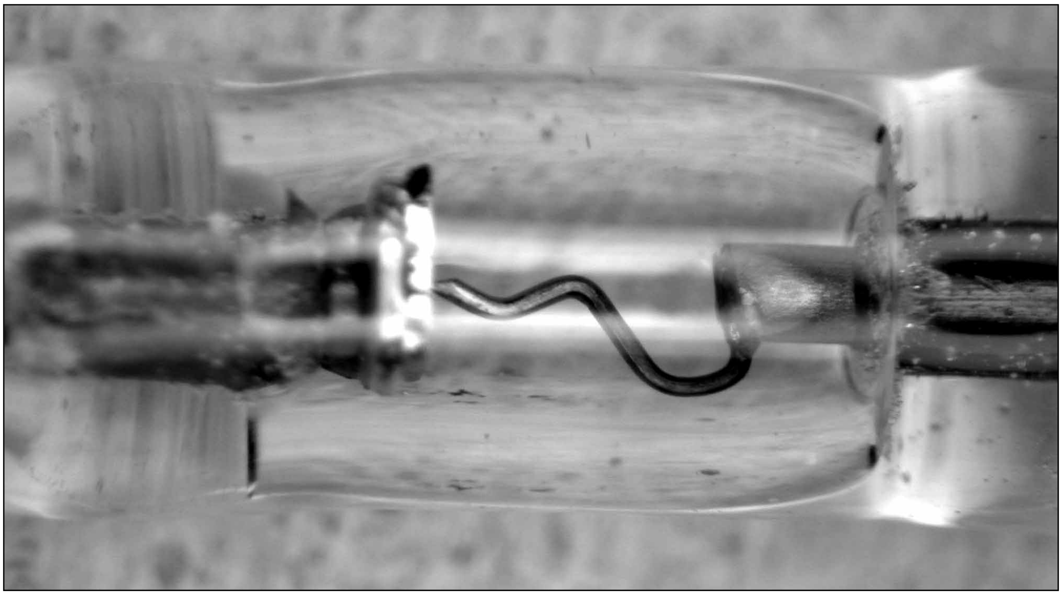
THE EARLY YEARS: BELL LABS

This theoretical attention to semiconductors intensified in the middle of the 1930s, spurred in part by practical considerations connected to the extension of radio technology. In this period scientists and engineers began to explore the use of much shorter wavelengths of radio waves for communications and other devices. In particular, researchers in the Bell Telephone Laboratories of AT&T, then a leading center of vacuum tube technology, found that vacuum tubes could not perform as rectifiers for these new, very short wavelengths. This failure led the Bell Labs researchers to a renewed interest in the use of semiconductors' rectifying abilities.

Bell Labs researchers soon focused on the use of one particular semiconductor, the element silicon, which had been the main constituent in many of the best cat's whisker, crystal detectors of radio's earliest days. Drawing on the accumulated studies of semiconductors and their electrical properties, the Bell Labs researchers, especially the chemist Russell Ohl, pursued a number of materials-centered issues en route to the development of an improved semiconductor point-contact rectifier for use in their experimental very shortwave radio systems. Ohl reasoned that the erratic behavior of earlier silicon cat's whisker detectors had been caused, in part, by chemical impurities in the crystals of silicon. Thus, through the late 1930s, Ohl and two metallurgists endeavored to obtain high-purity silicon by using high-temperature furnaces to further refine and form it into polycrystalline ingots.[4]

INTO SILICON

In 1940 Ohl and his Bell colleagues had succeeded in producing high-purity silicon polycrystalline ingots and had made several remarkable observations using the material. In short, the Bell researchers determined that the presence of different chemical impurities in silicon transformed its electrical behavior. They adopted the nomenclature of "P-type" and "N-type" silicon to express these differences. Chemical elements from the



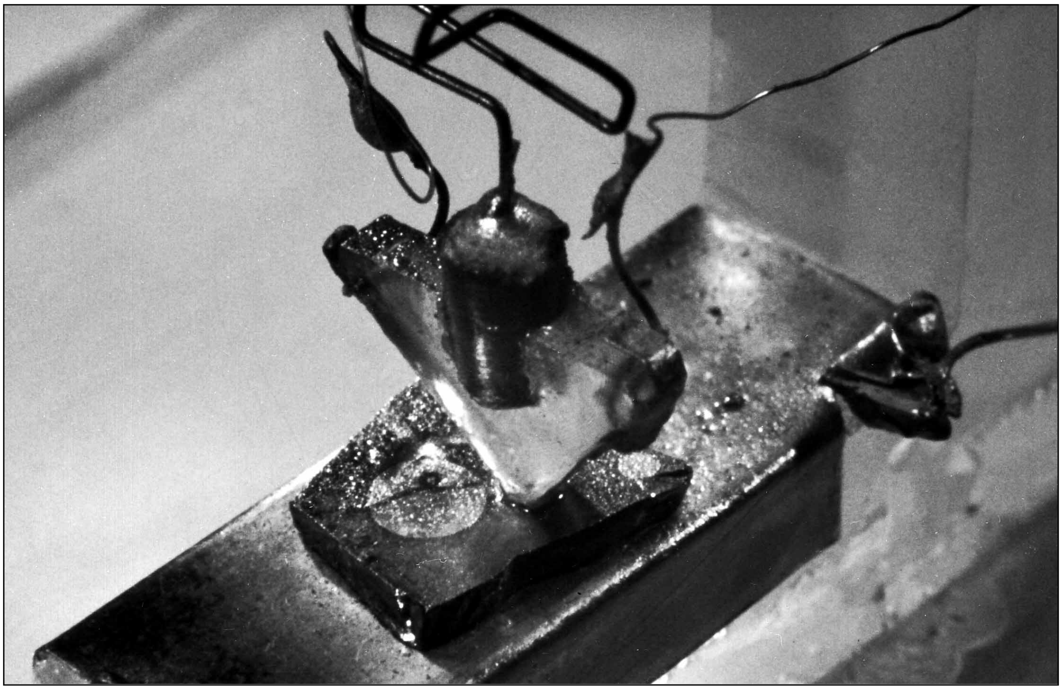
A point-contact rectifying diode. *Photo courtesy of Gil Toombes, Department of Physics, Cornell University.*

third-column of the periodic table such as boron and aluminum, when added to silicon, yielded material that had a *deficit* of electrons and was called P-type silicon, denoting this "positive" electrical characteristic. Conversely, when chemicals from the fifth-column of the periodic table were present in silicon, there was an *excess* of electrons and hence the N-type label for this "negative" property. Moreover, Ohl found that the junction between P-type and N-type regions in a single polycrystalline silicon sample acted as a rectifier, allowing current to flow across it in only one direction.[5]

During World War II very short wavelength radio waves were used to create vital radar systems, through massive, classified government programs. Point-contact rectifiers, using polycrystalline P-type and N-type samples of the semiconductors silicon and germanium, were developed by multiple groups working in academic, industrial, and government settings. These semiconductor rectifiers, or diodes, served as the crucial detector components in the radar systems developed and deployed during the war. To meet this demand for high-purity silicon, DuPont developed a process for producing ultra-pure silicon in the early 1940s.[6]

THE TRANSISTOR

In the immediate postwar period Bell Telephone Laboratories expanded its research and development activities on semiconductors and the new type of semiconductor or "solid-state" electronics that the silicon and germanium radar diodes represented. Not only did radar-like microwave communications represent a direct interest for the telephone company, but the new breed of electronic components also held the promise of competing with the then-dominant vacuum tube in terms of reliability, size, and electrical performance. The physicist William Shockley headed a group of physicists,



The first transistor (1947). *Property of AT&T Archives. Reprinted with the permission of AT&T.*

chemists, and engineers dedicated to improving the understanding of semiconductors in order to create new electronic devices.

In December 1947 two members of Shockley's group, Walter Brattain and John Bardeen—following a key suggestion by the group's chemist, Robert Gibney, and with theoretical guidance from Shockley—succeeded in creating just such a new electronic device: the transistor. The point-contact transistor was fashioned by two closely spaced gold contacts atop a slice of polycrystalline germanium, to which a large concentration of an N-type impurity had been added. Brattain and Bardeen's point-contact transistor was the first solid-state amplifier. The new semiconductor electronics was now in a position to overtake the vacuum tube. Like vacuum tubes, semiconductor devices could both rectify and amplify. Yet because of their simpler design, centered on using an appropriately fashioned piece of semiconductor material, they seemed far more reliable, were certainly far smaller, and were potentially better performing than the vacuum tube.[7]

SINGLE CRYSTALS

As word of the transistor spread through Bell Labs, it quickly captured the attention of Gordon Teal. Teal, a chemist in another section of Bell Labs, was particularly excited by germanium's role in the new transistor. Teal had earned his Ph.D. on investigations of germanium compounds, and he had a long-standing interest in using the element for new electronic devices. In contrast to the then-common polycrystalline ingots used to make the transistor, and the many rectifying diodes that Western Electric and other producers were manufacturing in volume, Teal was interested in developing a program at Bell Labs to produce *single crystals* of germanium. Like many others at Bell Labs, Teal realized that there were two key factors that determined the electrical behavior of semiconductor samples. One was the presence of chemical impurities, and the other was the presence of defects in the crystal structure of the semiconductor. From this perspective, the polycrystalline ingots of germanium used to make transistors and diodes were thickets of complex crystal defects.[8]

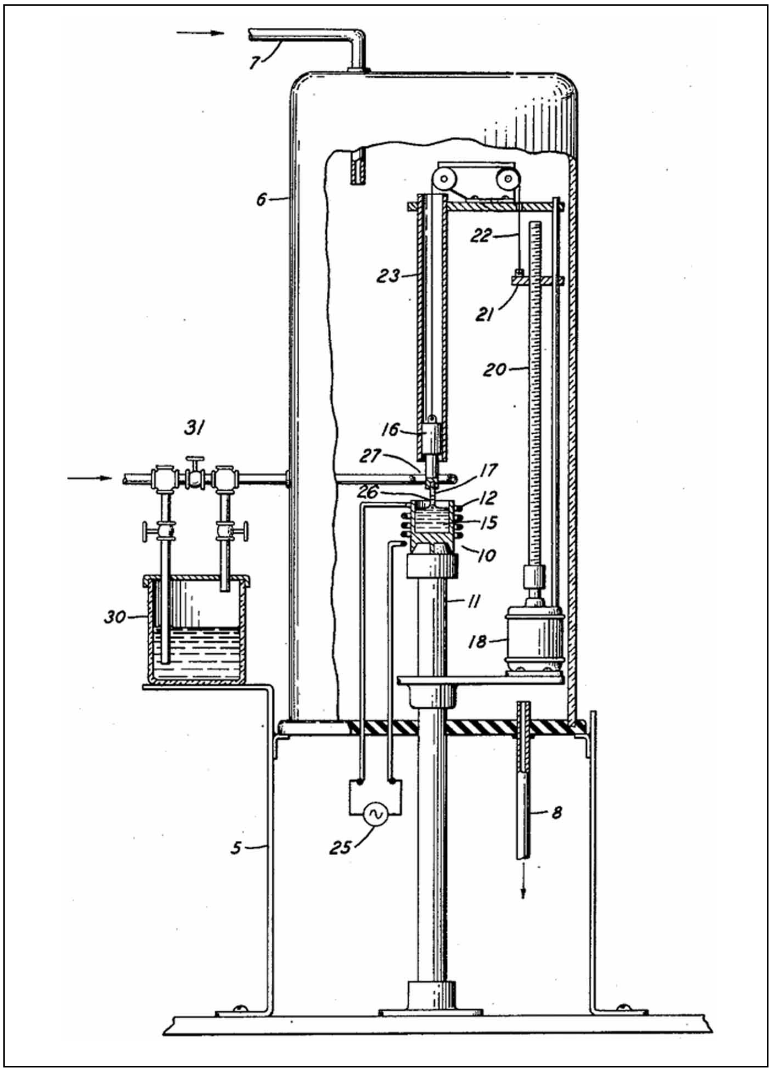
Teal used an analogy to the history of vacuum tube technology in his thinking about single crystal semiconductor materials. To describe the fundamental operation of the vacuum tube, researchers had found it necessary to perfect the vacuum within the tubes. With a perfected vacuum, the interfering effects of residual gasses were minimized, and the operations and behavior of vacuum tubes were more clearly studied. As a result of such fundamental studies, researchers had been able to construct enhanced forms of vacuum tubes. Teal reasoned that the vacuum of the tubes was analogous to the imperfections of semiconductor materials. If he could produce semiconductor material with a high degree of both chemical specificity and crystalline perfection, then this would provide researchers with a clear view of the fundamental operation of semiconductor devices such as the transistor. Improved semiconductor devices would result from these basic studies and the enhanced material.[9]

In the fall of 1948 Teal succeeded in establishing his single crystal program at Bell Labs and, in collaboration with engineer John Little, developed a new device for producing single crystals of germanium—a crystal grower. Teal's single crystal germanium did indeed possess superior electrical characteristics to its polycrystalline relatives. Within a matter of months William Shockley and his group, along with the majority of the researchers at Bell Labs, had become committed converts to Teal's single crystal germanium. During the next seven years, single crystal semiconductor materials—first, germanium and soon thereafter silicon—enabled Bell Labs researchers to generate an astounding roster of laboratory firsts in semiconductor devices and the processes for fashioning them.

Using single crystal germanium growing expertise provided by Teal, fellow Bell Labs chemist Morgan Sparks succeeded in creating the first junction transistor by 1951. Conceived by William Shockley, the junction transistor dispensed with the point-contacts of the original transistor. Rather, the new transistor's operation depended upon two junctions between P-type and N-type regions of semiconductor material in a single sample. Junction transistors came in two forms, PNP and NPN, standing for a sandwich-like formation of an N-type region between two P-type regions, or the converse. The first junction transistors were formed by growing single crystals out of a melt of germanium that was successively doped, or loaded, with impurities. For much of the 1950s the junction transistor persisted as the central semiconductor device.[10]

THE GROWTH AND SPREAD OF TRANSISTOR TECHNOLOGY

Soon after playing his role in the creation of the junction transistor, Teal and his coworkers revised their techniques for growing single crystals of the semiconductor



U.S. patent 2,683,676: Gordon Teal's crystal grower.

silicon. Silicon offered several potential advantages over germanium for making electronic devices, in particular its suitability for high-temperature applications. Silicon electronics would be heartier than germanium in the high temperature environments of potential military uses. At a technical conference in the spring of 1952, Teal reported that he had grown silicon single crystals at Bell, including a crystal containing a P-N junction. This was a key milestone on the road to a silicon junction transistor.[11] With both germanium and silicon single crystals available, Bell produced a cascade of new junction transistors in the next three years, including alloyed junction transistors and the important *diffused* junction transistors. In diffused junction transistors, dopant gasses were diffused into the bulk of the semiconductor crystal to form junctions. The closely spaced junctions that diffusion techniques were able to produce allowed for high-performance devices. In 1955 Morris Tanenbaum, a chemist at Bell, created the first doubly diffused silicon junction transistor, the form of transistor which would come to dominate the late 1950s and early 1960s in solid-state electronics.[12]

The Bell Telephone Laboratories of AT&T was a critical locus of innovation through the middle of the 1950s and thereafter, but in the early 1950s new entrants began to make significant contributions to semiconductor technology. Bell Labs itself had a strong hand in facilitating this diffusion of the transistor art. As early as September 1951 Bell Labs convened a symposium to provide detailed information about the transistor to interested academic and industrial researchers. Shortly thereafter, Western Electric began granting $25,000 patent licenses for the manufacture of transistors to any interested firm. In the spring of 1952 Bell Labs convened a large, eight-day symposium on transistor theory and manufacture for representatives of its first forty transistor licensees at Western Electric's Allentown, Pennsylvania, transistor manufacturing facilities.

The motives of the Bell System and its employees in these efforts to disseminate understanding of the transistor and manufacturing know-how were complex. In 1949 the U.S. government had launched a major antitrust suit against the telephone monopoly. With the development of the junction transistor set against the backdrop of the Korean War, there were active negotiations between the telephone giant and the U.S. military about the possible classification of transistor technology. Many Bell Labs semiconductor researchers thought that the potential of the new electronics necessitated active participation by a diverse technical community who would serve military needs as well as bring new products to markets quickly, markets that the telephone company's manufacturing arm, Western Electric, could not and would not serve.[13]

Across the 1950s, armed with transistor licenses and girded by active technical assistance from Bell Labs, a panoply of firms began to produce transistors in the U.S. and abroad. Among these firms were large vacuum tube manufacturers such as General Electric, RCA, Westinghouse, Sylvania, Raytheon, Philco, and Motorola. Other firms that had no previous experience in vacuum tube manufacture acquired licenses to enter the emerging market for the new semiconductor electronics. Among them were Texas Instruments, Transitron, Sprague Electric, NCR, and IBM. Teal left Bell Labs in 1952 to establish and lead Texas Instruments' entry into semiconductors. His success there was swift and enduring. In 1954 Teal's team introduced the first commercial silicon transistor—a grown junction device.[14] Texas Instruments' early position in the manufacture of silicon transistors set the stage for its strong position in the semiconductor industry that continues to the present.

MOVING WEST

In 1955, while the center of gravity of transistor activity was still on the East Coast, William Shockley left Bell Labs to establish a new semiconductor firm on the West Coast, bringing silicon to the region that would come to be known as "Silicon Valley." Working with Arnold Beckman, Shockley formed Shockley Semiconductor Laboratory as a subsidiary of Beckman Instruments. The founding aim of Shockley's new organization was the large-scale manufacture of silicon diffused junction transistors. Beckman had several interests in the new operation. Personally motivated by a wide-ranging enthusiasm for new technologies, Beckman had built an empire in the scientific instrument field through the creation of new chemical instrumentation that incorporated vacuum tube electronics. Moreover, Beckman Instruments had significant presence in the development of analog and digital computing systems. While Beckman Instruments was headquartered in Southern California, Shockley established his operation on the San Francisco peninsula in Palo Alto. This location was in the same town as Beckman's Spinco operation for biomedical instrumentation and placed Shockley Semiconductor in a region populated by a strong vacuum tube manufacturing industry.[15]

At Shockley Semiconductor, Shockley sought to recreate the mix of young, talented Ph.D.-level researchers that he had guided at Bell Labs, and which had led to the invention of both the point-contact and the junction transistors. Using his reputation and his well-established contacts with academic, industrial, and government organizations, Shockley recruited talent in physics, chemistry, metallurgy, engineering, and other disciplines from across the country. Recalling the key contributions of the chemists at Bell Labs, Shockley in particular sought a young, talented physical chemist. In 1956 he recruited just such a person: Gordon Earl Moore.[16]

A PORTRAIT OF THE CHEMIST AS A YOUNG MAN

Moore's family settled the small coastal town of Pescadero, some thirty miles southwest of Palo Alto, in the middle of the nineteenth century. When Moore was born in 1929, his father served as a constable and his mother's father ran a thriving general store. In the 1930s Moore and his family moved to Redwood City. Here his father became a long-serving deputy sheriff, and Moore became actively engaged with chemistry. Following exposure to a neighbor's chemistry set, Moore embarked on a precocious career as an explosives manufacturer through his early high school years. In a home laboratory in his parent's backyard, Moore used advanced chemistry texts to produce chemicals for a variety of bomb and rocket applications. The success of these early chemical endeavors set Moore on a career path in chemistry, which he pursued in undergraduate studies at San Jose State and the University of California, Berkeley.[17]

Moore continued along his path to chemistry by taking up graduate studies at the California Institute of Technology—the alma mater of both Beckman and Shockley. Working under Richard Badger, an infrared spectroscopist, Moore completed a Ph.D. thesis in physical chemistry and physics, on the analysis of the infrared spectra of nitrous acid and the photochemistry of nitric oxide. After Caltech, he took a position as a research chemist at the government's Applied Physics Laboratory (APL) that was managed by Johns Hopkins University. At the APL from 1953 to 1956 he conducted experimental research on the infrared analysis of particular molecules in flames. By 1956 Moore actively began to search for job opportunities that would lead him back to his native California. One of the opportunities that he explored was a position doing infrared spectroscopy connected to nuclear research at the government's Lawrence Livermore Laboratory, in Livermore, California—less than fifty miles from his childhood home in Redwood City. Lawrence Livermore offered Moore the post, but he turned it down because of its similarity to his work at the APL. For Moore, both lines of research were too far removed from practical application.[18]

William Shockley, drawing on the strength of his reputation and prior work for the government, was given access to Lawrence Livermore's employment files. He was intrigued by information he found about Moore—a Caltech physical chemist who had turned down a competitive post at a cutting-edge government laboratory. Not long thereafter, Shockley called Moore to offer him a position at Shockley Semiconductor. Moore was aware of Shockley's scientific standing, having listened to him lecture about the transistor in Washington, D.C. He accepted Shockley's offer and returned to California, stopping along the way to learn about transistor technology through meetings at Bell Labs and the University of Illinois arranged by Shockley.[19]

SHOCKLEY'S LAB

At Shockley Semiconductor, Moore joined an impressive group of young researchers. Robert Noyce, a physicist, had the most experience with semiconductors, having worked with Philco on the manufacture of germanium transistors. Jean Hoerni, another physicist, had been recruited from Caltech and held two physics Ph.D.s, one from Cambridge and the other from the University of Geneva. Jay Last and C. Sheldon Roberts held Ph.D.s from the Massachusetts Institute of Technology in physics and metallurgy, respectively. Over the course of the next year, the group worked to produce silicon junction transistors using diffusion processes. However, perhaps guided by Texas Instruments' and other manufacturers' successful development of the silicon transistor business, Shockley led his organization into several new directions, blurring the early focus on the manufacture of silicon diffused junction transistors. These strategic changes, coupled with divisive management practices by Shockley, resulted in the formation of a group of dissatisfied researchers in the organization. The group's attempts to resolve differences with Shockley and Arnold Beckman failed, and eight members of Shockley Semiconductor resigned (Last, Roberts, Hoerni, Moore, Noyce, Eugene Kleiner, Julius Blank, and Victor Grinich).[20]

FAIRCHILD SEMICONDUCTOR: THE BIRTH OF THE PLANAR

Far from disbanding, the group stayed intact and in the fall of 1957 established Fairchild Semiconductor in Palo Alto, as a subsidiary of the East Coast-based Fairchild Camera and Instrument Corporation. Fairchild Semiconductor focused on the manufacture of silicon diffused junction transistors. The founders divided the technological challenges among themselves in a crash program to develop a first product. Moore concentrated on manufacturing, specifically the issues surrounding diffusion processes, forming metal contacts to the silicon transistors, and the final packaging and assembly of the devices. In 1958 with an order in hand from IBM, Fairchild Semiconductor introduced the first commercial double diffused silicon transistors. Not only was Fairchild's transistor the only such device available, but it was also engineered to meet the stringent performance and reliability conditions demanded by IBM for its use in a military, airborne computing system.[21]

In the next two years the market for silicon transistors rapidly expanded, driven primarily by military consumption but also by growing commercial applications. In 1958 silicon transistors constituted a $32 million business. In 1960 the figure grew to roughly $90 million. While this market was served by many producers other than

Fairchild Semiconductor, such as Texas Instruments, Fairchild's sales grew remarkably. In 1958 the firm sold $500,000 worth of its silicon transistors and diodes. Two years later it achieved $21 million in revenue.[22] The era of silicon electronics had arrived.

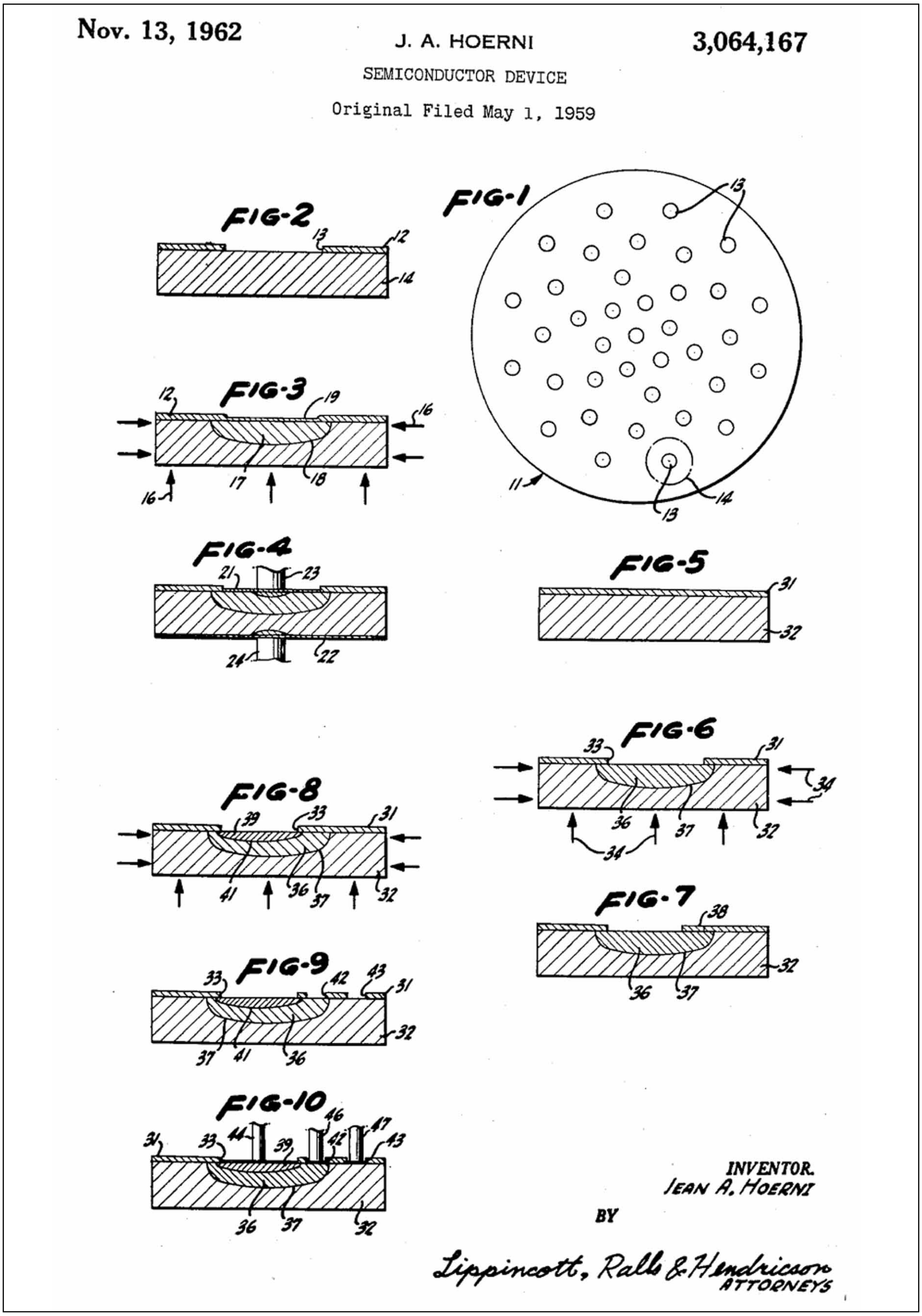
As Fairchild's production and business grew, Moore assumed more responsibilities for the correspondingly expanding organization. He served as the head of engineering to 1959, then became director of research and development. Moore was deeply impressed when, in 1959, Hoerni developed a new process for manufacturing silicon transistors—the planar process. Hoerni's invention entailed using the readily forming oxide layers on silicon in new ways to fabricate transistors, tame the electrical behavior on their surfaces, and protect the final transistor from disruptive contaminants. Fairchild's new planar transistors, introduced to the open market during 1959 and 1960, offered great advantages in performance and reliability.[23]

INTEGRATED CIRCUITS

While Moore witnessed a significant advance in semiconductor technology developed within Fairchild Semiconductor in 1959, resulting from Hoerni's planar process, he and others at Fairchild noted a significant advance made by Texas Instruments during the same year. Jack Kilby of Texas Instruments had taken a major stride forward in the miniaturization of electronics, indicating that an integrated circuit built from semiconductor materials was possible.

For over a decade individual transistors had held a size advantage over vacuum tubes. With small discrete transistors, engineers fashioned ever-more compact, complex electronic circuits for a variety of military and commercial applications. However, as engineers produced increasingly complex circuits using many discrete transistors—along with such other components as diodes, capacitors, and resistors—their concerns about a "tyranny of numbers" began to grow. Simply put, the number of components and their interconnections involved in these circuits would eventually imperil the reliability of the circuits. With so many parts that could fail, engineers felt the closing in of an upper limit to possible complexity. By the middle of the 1950s the concept of a "monolithic" circuit gained credence in the semiconductor electronics community. The idea of the monolithic circuit was to create a complete electronic circuit from a single piece of semiconductor material, different regions of the material producing the different functions of components such as transistors, resistors, and capacitors. Not only would such a monolithic circuit avoid the tyranny of numbers in terms of interconnections, but it would also open up new possibilities for the miniaturization of complete electronic circuits. Many members of the technical community were skeptical of the concept, for it too faced its own tyranny of numbers, a "tyranny of yield."[24]

Yield was a primary economic factor and therefore a central concern of the semiconductor industry. Discrete silicon transistors, like Fairchild's planar transistors, were fabricated in batches, with multiple transistor structures formed on a single wafer of silicon. Yield was the percentage of usable devices formed on a wafer. The lower the yield, the higher the manufacturing cost per device and the lower the resulting profit. From the perspective of the semiconductor industry in the middle 1950s,



Nov. 13, 1962

J. A. HOERNI

3,064,167

SEMICONDUCTOR DEVICE

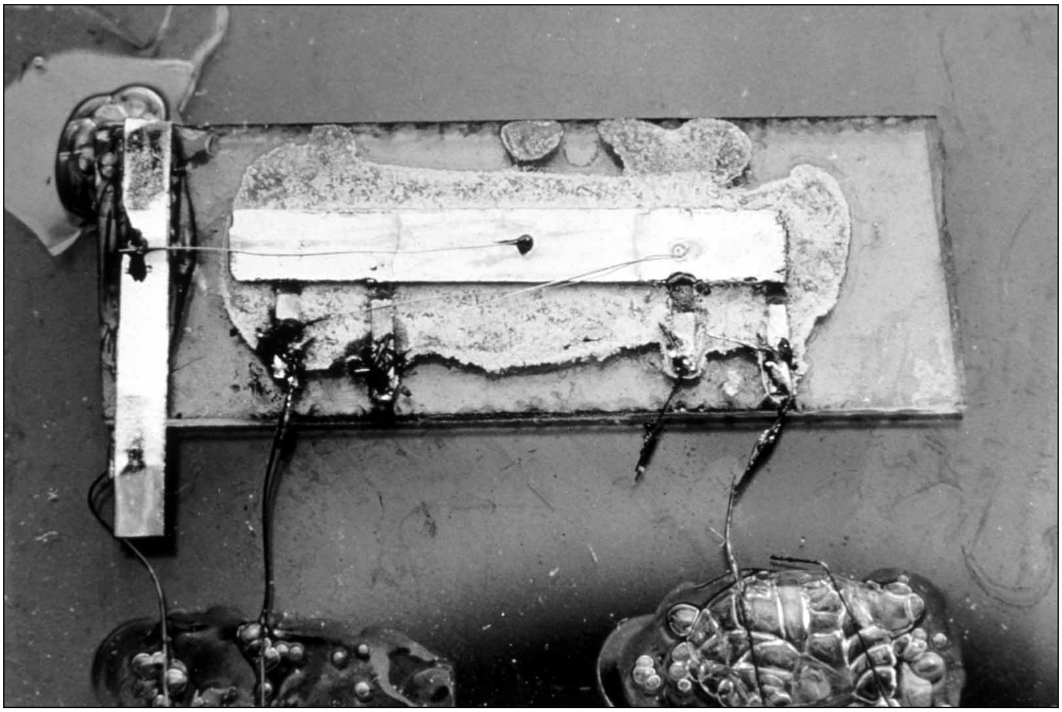
Original Filed May 1, 1959

INVENTOR.
JEAN A. HOERNI

BY

Lippincott, Ralls & Hendricson
ATTORNEYS

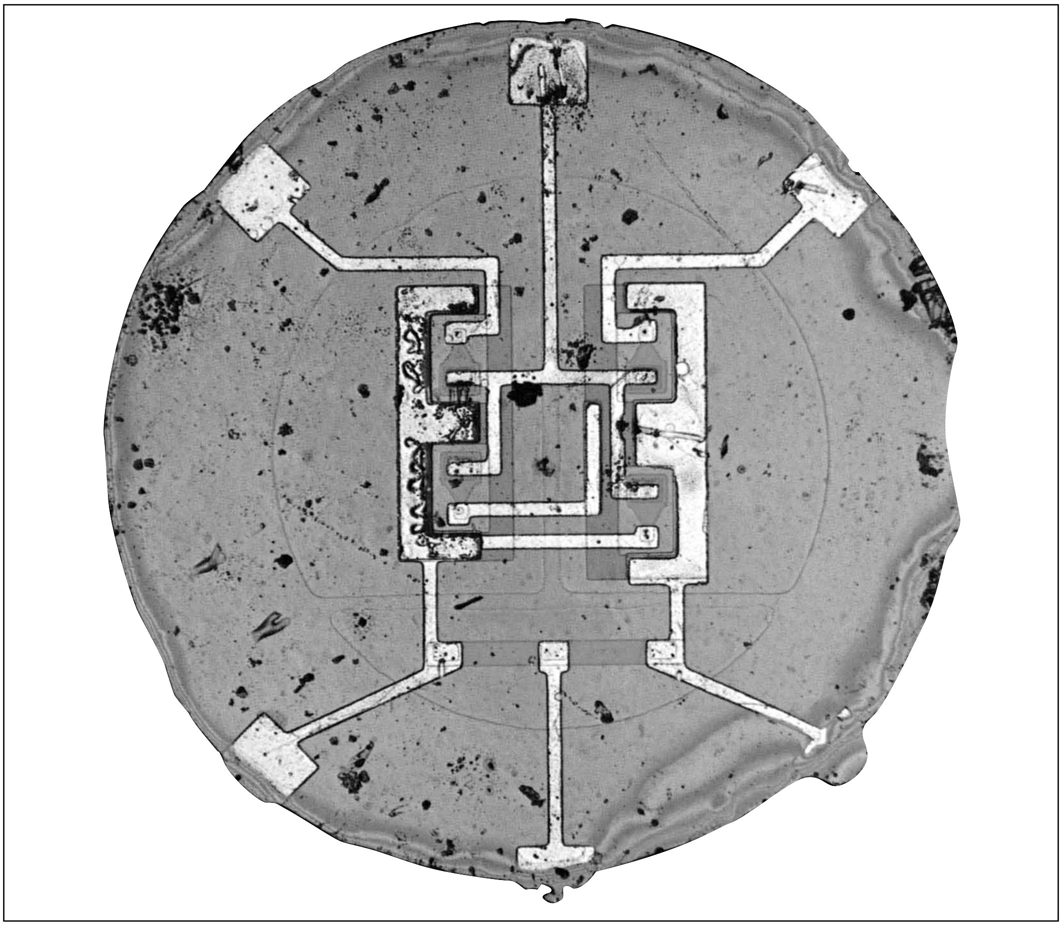
U.S. patent 3,108,914: the planar transistor.



Jack Kilby's integrated circuit. *Courtesy of Texas Instruments*.

the monolithic circuit concept, in terms of yield, appeared impractical. The industry had a difficult enough time achieving reasonable yields for discrete transistors, and technologists could not envision practical approaches to achieving economical yields for fabricating monolithic circuits given the current state of the manufacturing art.[25]

In the fall of 1958 Texas Instrument's Jack Kilby succeeded in demonstrating that the monolithic concept was a practical possibility, though he did not address the issue of yield. He produced an integrated circuit—a linear oscillator involving a transistor, a resistor, and a capacitor formed from a single slice of germanium crystal. The various regions of the germanium that functioned as circuit elements were interconnected by gold wires "flying" above the germanium material. Noyce at Fairchild Semiconductor thought the Texas Instruments achievement to be impressive but not suited to actual manufacture. It did not answer the challenge of the tyranny of yield. But Noyce did not leave the matter at that. The planar transistors that Fairchild Semiconductor had recently introduced were novel for their use of a protective, stabilizing oxide layer covering the entire surface of the device. At the start of 1959 Noyce conceived of another use for this oxide layer. His idea was to use it as an electrical insulator, atop of which metal interconnections could be laid to interconnect circuit components in a new, planar form of silicon integrated circuit. Not only would Noyce's planar integrated circuit benefit from circuit elements formed in silicon by Hoerni's new diffusion-based process, it would also employ metal interconnections attached to the insulating oxide surface. Side-stepping Kilby's germanium and flying wires, Noyce's planar



An early silicon planar integrated circuit (1961). *Courtesy of Fairchild Semiconductor.*

integrated circuit turned out to be practical for manufacture because it could dispose of the tyranny of yield. In 1960 within Moore's research and development laboratory at Fairchild, Jay Last led the development effort to create the planar integrated circuit. Last's efforts led Fairchild Semiconductor to introduce an entire suite of planar integrated circuits to the open market in 1961, the "micrologic" family. Texas Instruments followed suit, introducing its own line of planar integrated circuits later in that year. The microchip age had been launched.[26]

As had been the case with silicon transistors, between 1961 and 1965 the market for the integrated circuits greatly expanded. In 1961 Fairchild Semiconductor earned $500,000 on integrated circuit sales. In 1966 Fairchild and other integrated circuit producers on the San Francisco peninsula garnered $60 million from sales of microchips, representing half of the U.S. market.[27]

While the market for silicon integrated circuits was growing in the early 1960s, Moore and others in the semiconductor industry experienced customer resistance to and skepticism of the new microchips. From his vantage point as the head of Fairchild

Semiconductor's research and development operation—perhaps the leading-edge center for integrated circuit innovation—Moore had a much rosier perspective of microchips' manifest destiny. For him, they were the route to further miniaturization and increasingly complex electronic circuits. They were the vehicle to significantly cheaper and more powerful electronics. In addition to advancing the new technology itself, a major issue facing Moore was getting his message across to potential customers and the semiconductor industry. Finally in early 1965 came the opportunity to publicize and advance the cause.[28] This opportunity would lead to Moore's publication of what has come to be known as Moore's law in the magazine Electronics in 1965.

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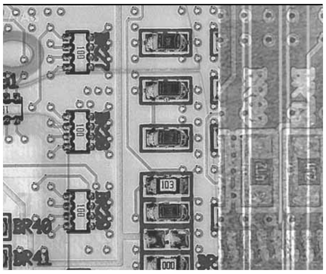
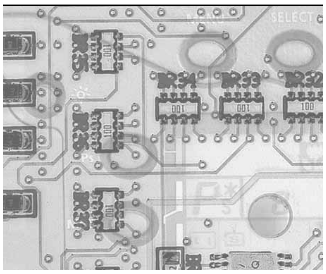
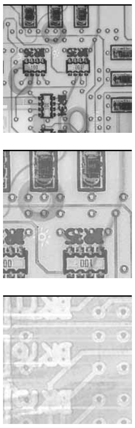


PART TWO

ARTICULATIONS





CHAPTER 3

A Clear Voice: The Origins of Gordon Moore's 1965 Paper

David C. Brock

The preconditions for Gordon Moore's development and publication of Moore's law in 1965 lie in two interconnected historical crosscurrents of differing scope and magnitude. Chapter Two, "The Backdrop to Moore's Law: Developments in Semiconductor Electronics to 1965," details one of these contexts. It outlines the emergence of silicon semiconductor technology in the middle of the twentieth century as the continuation of a two-century connection among the worlds of chemistry, electricity, and electronics. This context is paramount, since Moore's law represents a key insight into and motivator for the development of semiconductor technology. The present chapter explores a second essential context for understanding the origins of Moore's law: the engagement of the silicon community with the practice of miniaturization in the 1960s and the associated consequences of miniaturization for the rapidly emerging technology of integrated circuits that were foreseen by certain leaders of the semiconductor industry. Miniaturization and the discussion of its potential for integrated circuits was the immediate context out of which Moore's law arose.

Shrinking Discussions: Miniaturization

The first half of the 1960s was a period of great expansion for both the technology of and the market for silicon integrated circuits. For the semiconductor community, the integrated circuit became a central focus of research, discussion, and speculation. At the center of this discussion was the issue of the miniaturization of integrated circuits and the economic and technological potential that this trend could unlock. While miniaturization of integrated circuits was new—these devices had only been developed in the closing years of the 1950s—miniaturization was nevertheless old hat for the semiconductor community. In fact, it had been the industry's watchword since the middle of the 1950s in the province of discrete transistors.

Just as the small size of the earliest transistors gave them an upper hand over vacuum tubes, miniaturization was a key advantage that successive generations of silicon transistors had over one another. When researchers succeeded in making silicon transistors smaller, they could operate faster. Given a reliable manufacturing process, each transistor became cheaper to produce. Silicon transistors were—from their beginnings to the present day—fabricated in a batch process. Using photolithographic, mechanical, and chemical processing steps, manufacturers created multiple transistors on a single wafer of silicon. The ultimate measure of such a manufacturing process was its yield, the ratio of working devices to defective devices produced on each wafer. Given a satisfactory yield, a smaller transistor meant that more of them could be made on a single wafer, making each one cheaper to produce. Higher performing, cheaper discrete transistors were used by the semiconductor industry to open up new applications and markets for semiconductor electronics through the 1950s.[1]

By 1960 miniaturization was a fundamental issue for semiconductor technology and its industry. It had become, moreover, a central factor in the semiconductor community's discussions surrounding the new integrated circuits that had been touted in 1959 by Texas Instruments as the first realization of the "monolithic" circuit ideal. Enhanced performance and reduced cost—the same factors that had made miniaturization so important in the development of discrete transistors—were quickly recognized as key ingredients in the dawning technology of integrated circuits. At the 1960 Solid-State Circuit Conference—the annual meeting was a prominent gathering ground for the semiconductor community—there was an intense discussion of miniaturization and the future of integrated circuits. The discussion took place at the very conference session where representatives from Moore's research and development laboratory at Fairchild Semiconductor debuted their manufacturable planar integrated circuit: a seminal breakthrough.

VOICES IN THE MINIATURIZATION CROWD: ENGELBART, LAST, AND MOORE

On Friday morning, 12 February 1960, a group of young men gathered in the University of Pennsylvania's Irvine Auditorium for a session of the Solid-State Circuit Conference (SSCC), titled "Microelectronic Considerations." Five papers were presented at the session, representing recent work conducted at some of the most important centers for the development of semiconductor technology. The session was chaired by J. R. Nall, who had recently joined Fairchild Semiconductor. Nall would have seen the faces of any number of his Fairchild Semiconductor colleagues in the Irvine Auditorium that morning. His colleagues Jay Last (one of the founders of the firm), Isy Hass (an engineer working closely with Last), and Robert Norman (a key sales and marketing executive) had prepared a paper important for the firm, "Solid-State Micrologic Elements."[2] Another of Fairchild's cofounders, Victor Grinich, had participated on a panel for one of the conference's informal discussion sessions late into the evening before. Grinich may have stayed on to see the reaction to his colleagues' paper. Moore, yet another of the Fairchild cofounders, may have been in the auditorium that morning as well. His attendance would have been consonant with the important public announcement of Fairchild's integrated circuit products. He recalls having heard one of the first speakers of the session discuss the ideas presented that day, although he is unsure if he heard it in Philadelphia or elsewhere.[3] Leading off the session was a paper by Douglas C. Engelbart, then a researcher at the Stanford Research Institute, titled "Microelectronics and the Art of Similitude."

Recently, Engelbart has received a great deal of attention for his pioneering contributions to the development of computing.[4] In the early 1950s Engelbart developed a vision for computing that anticipated many features of today's world of networked personal computers. In the 1960s he invented the computer mouse as an input device, developed many of the present-day standard elements of graphical computer interfaces, and developed the first word processor. Today, Engelbart continues his work to advance the use of computers to "augment" human intelligence.

In 1955 Engelbart earned a Ph.D. in electrical engineering from the University of California, Berkeley. Before his graduate work, he had served as an electrical engineer at the National Advisory Committee for Aeronautics' Ames Laboratory. While working at Ames, Engelbart developed his vision for future computing. His decision to study at Berkeley was closely connected to this vision. After receiving his Ph.D., Engelbart taught at Berkeley for two years. He also filed patents on both a display device for use with digital computers and gas-tube components for computers. He moved to the Stanford Research Institute in 1957 and continued his work on devices for digital computers, especially designing systems based on magnetic memory technology to perform logic functions.

Engelbart's interest in electronic devices extended beyond magnetic logic. He had been following several miniaturization trends in electronics, specifically in the manufacture of discrete transistors and the widely touted "molecular electronics" push by the U. S. Air Force. The push envisioned a future of highly miniaturized devices or "functional blocks," of material that performed the function of entire circuits. Engelbart was also interested in the very recent work by Texas Instruments on integrated circuits. He saw that silicon semiconductor technology and new exploratory semiconductor techniques envisioned in the molecular electronics program were on a path to the creation of highly miniaturized electronic components and circuits. His paper at the SSCC, "Microelectronics and the Art of Similitude," was an alert to the semiconductor community that miniaturization's drastic change in scale would necessitate new considerations.[5]

In the written summary of his talk, Engelbart began

> Several programs are afoot to develop materials-handling and fabrication techniques suitable for constructing extremely small devices and circuits. The techniques developed earliest will, very likely, not be capable of fabricating scale models of many of the present types of devices and circuits. There is likely, then, to be a search for new components appropriate to the available materials and fabrication techniques. Another reason, generally overlooked, for evolving new devices is that effects of size scaling, long a familiar concept in some fields, but rarely involved in electron-device engineering, will make

> some devices inoperative at micro-scale; and will require most others to be modified in ways which will baffle the intuition and the understanding which has been developed in working with normal-sized devices.[6]

Engelbart's argument was a simple syllogism, with two premises and a conclusion. His first premise was that the function of an electronic device depended on the relationship between a number of physical phenomena and properties. His second premise was that miniaturization would significantly change some of these physical phenomena and properties. Therefore, new designs for devices would be required to realize the same electronic function at this highly miniaturized scale, and novel physical phenomena at this scale would open the door to the design of entirely new kinds of devices. For the coming era of increased miniaturization, he recommended that the semiconductor community adopt the engineering practice of "similitude."

In brief, engineers used similitude for working with scale models—in the development of airplanes, submarines, ships and the like. Many factors in their dynamics and behavior involved dimensional constants, that is, they depended on length, weight, and time. In order to extrapolate from the information that they gathered from working with small-scale models to the full, large-scale actual device, engineers translated their description of the dynamics and behavior involved into *dimensionless* constants. This translation was the practice of similitude. Like the translation of natural language, similitude involved well-grounded rules as well as intuition-based creativity. Consequently any number of translations of a dimensional to a dimensionless description was possible.[7]

Engelbart's basic contention in 1960 was that the semiconductor community could learn much from their fellow engineers about the use of similitude, but that they needed to operate it in the reverse direction. Similitude had traditionally been used for going from the small to the large. Engelbart suggested that it would be an advantageous tool in moving from the large to the miniature. As he surmised

> Several benefits can result from making use of similitude. It provides a methodical ways of determining which electronic-device techniques will be useable on a given miniaturization scale. . . .Another point of interest arises when the shift in the relationship between the different phenomena is noted as the size is scaled. This shift makes some devices ineligible for microminiaturization, but it also opens up fresh phenomenological relationships at each new size scale for an investigation in terms of new devices.[8]

Engelbart's remarks were an exploration of the consequences of future miniaturization in integrated circuits and not, as has been claimed, an anticipation of the argument that Moore published five years later, now known as Moore's law.[9] In his original manuscript and the published version of his 1965 paper, Moore presented an unusually clear, accessible argument that integrated circuits would dominate the future development of electronics because of cost and performance factors entailed by continued miniaturization in the technology of silicon planar integrated circuits. Rather than anticipating Moore's law, Engelbart's 1960 presentation is a prime example of the type of insightful discussion about the potentials of integrated circuit miniaturization from which Moore's argument emerged. Engelbart's contribution was but one voice in a chorus of comments out of which Moore's law would emerge.

Following Engelbart's paper in the 1960 SSCC session came the first public announcement of Fairchild Semiconductor's integrated circuit products: the paper "Solid-State Micrologic Elements," prepared by Jay Last and his two Fairchild colleagues. The Fairchild trio began: "If one examines a typical transistor, with the can removed, it will be noted that it looks more like a pea on a dinner plate. Thus it is feasible to consider packaging complete logical functions within a transistor package. . . . A family of high-speed, low-power micrologic elements for digital computer applications has been developed."[10] The trio went on to describe the silicon planar integrated circuits that they had developed: a flip-flop, a gate, an adder, and a shift register. Yet the Fairchild paper did not stop with what had already been accomplished: "The feasibility of using the uncased elements for packaging the logic system of a typical real-time digital computer in a volume of the order of 1.5 cubic inches will be demonstrated. This corresponds to a packaging density of the order of 1.5 million logic functions per cubic foot." As with Engelbart's paper, the potential of miniaturized, integrated logic circuits was foregrounded. However, Engelbart was concerned with a vision of the *possible*. The Fairchild paper made an argument about what was *feasible*, given what they had achieved with their new line of revolutionary integrated circuits.

From 1960 to 1964 the semiconductor industry quickly gravitated to Fairchild Semiconductor's breakthrough integrated circuits, with many players adopting the firm's silicon planar integrated circuit approach. The market for silicon integrated circuits expanded significantly, almost exclusively on the basis of military sales. Prices for integrated circuits were still above what many systems producers were accustomed to paying for electronic components. The technology was new, the volumes were relatively low as compared to discrete devices, and the integrated circuits were most frequently built to stringent military specifications for performance and reliability. Moreover, integrated circuits required potential customers to adopt a new mode for evaluating the cost of electronic components, one that encompassed the costs associated with a set of the equivalent discrete components and the labor to interconnect them into a complete circuit.[11]

By 1964 the new market for silicon integrated circuits was still largely limited to the military sector, but during the four years since 1960, many leaders in the semiconductor community had become convinced that integrated circuits were the future of electronics. To the same degree that the vacuum tube stood as the symbol of electronics' past and the silicon transistor stood as the icon of its present, these leaders believed that silicon integrated circuits would constitute electronics' future. Although history proved them correct, the situation was far from preordained in the opening months of 1964.

ENVISIONING AN INTEGRATED FUTURE IN 1964

In the first half of that year, the Institute of Electrical Engineers (IEEE) held its annual international convention in New York City. As part of the event, convention organizers gathered a collection of leaders from the semiconductor industry for a special session devoted to integrated circuits and their future potential. It was a forum where these leaders, convinced of the importance of integrated circuits to the electronic future, could communicate their vision to the assembled professionals. Their audience included those who would build this future—both as makers and as users of integrated circuits.

In June 1964 the IEEE published edited versions of these remarks in a special issue of *IEEE Spectrum*, the journal sent to every member of the electrical engineers' professional organization. The entire issue was devoted to "Integrated Computer Circuits."[12] The industry leaders' remarks were technical articles, though aimed at a broad audience of semiconductor specialists and nonspecialists alike. Each leader expounded, in their personal idiom, the vision of an integrated circuit future based on economic and technological imperatives. C. Lester Hogan, then the vice-president and general manager of Motorola's semiconductor products division, was the first to present his version of this shared vision.

Hogan attempted to give system producers a new framework for evaluating the cost of integrated circuits. "[It] appears that monolithic silicon," Hogan said, "will have the edge in digital circuit applications for cost alone."[13] He then outlined this cost argument using an idealization of the then-current technology for making silicon integrated circuits. Hogan estimated that the direct cost for the processing steps required to fabricate integrated circuits on a one square-inch wafer of silicon was $10. With a yield of 100 percent, such a wafer could produce 400 individual integrated circuits at a direct manufacturing cost of $0.025 each. While excluding design, packaging, and other indirect costs, Hogan's idealized picture placed an entire integrated circuit into direct price competition with a single, traditional discrete transistor. He concluded: "Any method that requires the connection and attachment of individual transistors to a circuit can never achieve the low cost of the monolithic silicon approach to integrated circuits, provided the yield percentages are comparable." Hogan's message was that the labor and manufacturing costs of the traditional approach of building circuits from discrete components would no longer be cost efficient.

The next industry leader to present his version of the integrated circuits vision was Robert Noyce, cofounder of Fairchild Semiconductor and inventor of the planar integrated circuit. Noyce's contribution, "Integrated Circuits in Military Equipment" echoed Hogan's cost leitmotif but tuned to the then-dominant military market. For the military market, Noyce noted, discrete transistors produced in relatively small quantities were then priced in the $3 to $5 range. He calculated that the prevailing pricing for integrated circuits translated into a typical price of $4 per transistor in integrated circuits produced in similarly small quantities. In larger quantities the transistors in integrated circuits cost only *half* the lowest typical price for their discrete counterparts, he added. Given that the military market had consumed essentially all of 1963's integrated circuit production and was poised to consume 95 percent of the 1964 production and possibly as much as 55 percent of all integrated circuits by 1970, Noyce argued that in this vast market integrated circuits would prosper on the basis of cost.[14] Noyce's was a crisp assertion of the continuation of silicon integrated circuits' cost competitiveness in its dominant, existing market.

Following Noyce, Leonard Maier, the general manager of the semiconductor products department of General Electric, also sounded the same tune of cost competitiveness. Starting with digital computer systems, Maier surmised that the 1964 pricing of high-volume, logic integrated circuits already rendered them "lower than for comparable circuits assembled from discrete components," and that this price advantage would grow over time.[15] Maier also forecast a cost tipping point for broader uses of integrated circuits in manufacturing. Specifically, Maier looked for uses of integrated circuits in what he termed "industrial equipment," that is, as components in communications gear and instrumentation and in control systems for the broad range of industrial manufacturing tools and equipment. "For the many applications in the industrial electronics field," he wrote, "semiconductor integrated circuits will be very cost competitive during the next five years and should have a clear competitive edge by 1974 in all except the smallest volume applications."[16] Maier's forecast about the cost competitiveness of integrated circuits expanded beyond the military market to the huge economic sector of industrial manufacturing.

J. E. Brown, the vice-president for engineering of the Zenith Radio Corporation, followed Maier in sequence and theme. Brown looked at the prospects for integrated circuits in consumer products. His message was simple and brief: There were broad possibilities for the use of integrated circuits in consumer products, far beyond their immediate and obvious applications in products such as hearing aids, televisions, and radio sets. While Brown held that there were no significant technical hurdles for integrated circuits to overcome in the area of consumer product applications, he noted that integrated circuits were not yet cost competitive with existing electronic components used in consumer products: "The problem at this time is somewhat more economic than scientific: reduction of cost is the key to the opening of vast new fields of application."[17] Brown's message was that the consumer products market would accept integrated circuits if and when they could be produced at a low enough price.

C. Harry Knowles, the manager for Westinghouse's molecular electronics division, followed with a forceful, speculative, and wide-ranging presentation. Knowles set out a new version of the tyranny of numbers that had previously dogged the concept of integrated circuits. For Knowles actual integrated circuits faced a new tyranny of complexity and cost: "The complexity problem facing both designers and users of integrated circuits is that cost increases as each component becomes more complex, as the number of components on a block increases." Knowles saw a solution to this "complexity problem" of cost in the continued development of semiconductor manufacturing technology: "In each case, as the technology improves, the cost decreases. . . yield improves, and cost drops."[18]

To illustrate this position, he produced a graph (Figure 1) plotting the "cost per function" of an integrated circuit against the "complexity" of the integrated circuit. Knowles graph is static, that is, it represents a single moment in time during the development of manufacturing technology. His metric for cost, on the vertical axis, is simple: U.S. dollars. His measure for integrated circuit complexity is less direct, gauged by the number of pins on the packaging of an integrated circuit, rather than a feature of the integrated circuit itself. Knowles's graph was intended to show that at a given stage of manufacturing technology, there was a particular degree of complexity associated

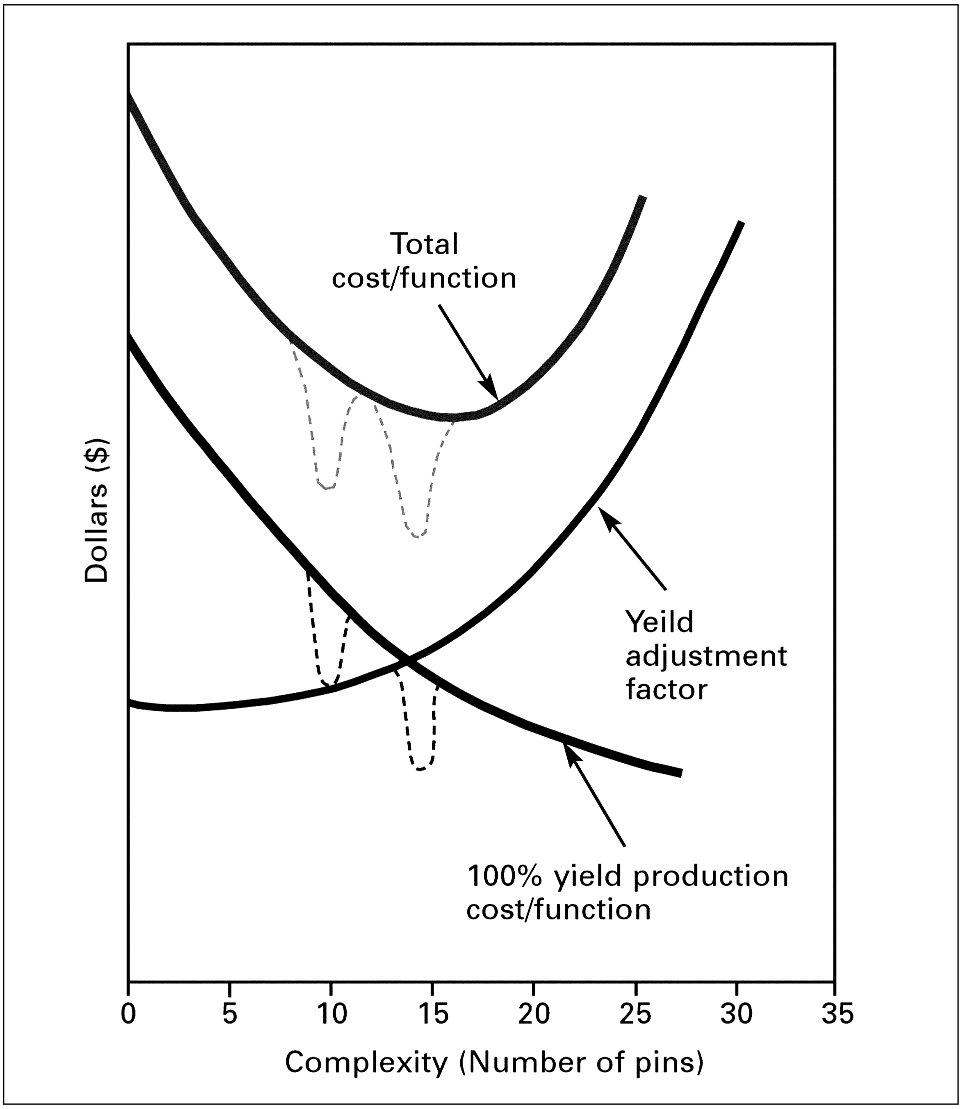


FIGURE 1. Cost plotted as a function of complexity as evidenced by the number of pins in a package. Total cost per function is a minimum at a complexity of 10 to 14 pins. Source: Harry Knowles, "Research and Development in Integrated Circuits," *IEEE Spectrum*, June 1964, page 77.

with a minimum cost per function. The top curve of the graph, the total cost per function curve, was the product of the lower two curves—one representing cost per function assuming a perfect, 100 percent yield, the other representing the actual diminishing yields that the manufacturing technology would exhibit for increasingly complex integrated circuits. The dashed line "downward perturbations" are artifacts of Knowles's indirect metric for integrated circuit complexity, the number of pins on the integrated circuit's package. The downward spurs on the curve represent manufacturing cost reductions associated with the mechanical automation of the packaging process for

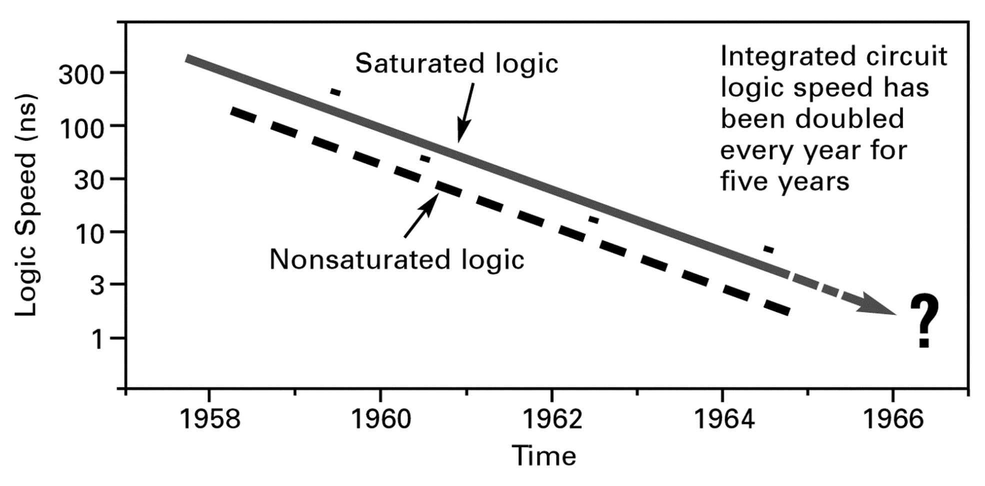


FIGURE 2. Average propagation delay per stage as a function of years for both saturated logic and nonsaturated circuitry. Source: Harry Knowles, "Research and Development in Integrated Circuits," *IEEE Spectrum*, June 1964, page 78.

integrated circuits, constructed around particular standardized packages having a set number of pins.

Knowles thus offered a graphic view of the relationships between yield, complexity, technology, and cost for integrated circuits. While the graph was temporally static, Knowles provided a description of how such a graph would change as integrated circuit manufacturing technology developed. He explained that technology development would push the "yield adjustment curve" outward to the right of the graph, producing better yields at higher complexities. The result would be a shift of the total cost per function curve down on the cost scale, and out to higher complexities. Knowles's implicit message was that the point of minimum cost per function would be attained, over time, at successively higher complexities.

Following this future-oriented cost argument, Knowles introduced the issue of performance, namely the speed of logic circuits in digital computers. Logic speed, Knowles noted, was the "principal integrated circuit interest. . .in digital computers,"[19] that is, the primary measure of logic circuit performance in computing. Knowles charted logic speeds, as measured by propagation delay, from the earliest integrated circuits of 1958 through the latest products of 1964 (Figure 2). Knowles concluded that integrated circuit performance had grown dramatically and steadily since the inception of the new technology: "Speed has doubled every year over the past seven years on the average."[20] This was exponential progress.

Knowles's presentation of 1964 anticipates some of the central features of Moore's 1965 publication. Knowles attempted to present the vision of the integrated circuits future through two distinct arguments: one of cost, the other of performance. He argued that at any given time in the progress of manufacturing technology, there was a particular level of integrated circuit complexity associated with a minimum cost per function. Moreover, he implied that this economically optimum complexity point would move, over time, to higher levels. Concerning the matter of performance, he said that logic speed had doubled every year for seven years, and that, "[as] transistors. . .can be made smaller. . .the speed of the circuits will be increased."[21]

In contrast, Moore—in his publication of 1965—made an integrated argument, connecting cost with performance. He focused on the economic advantage that integrated circuits would gain over time, and the inherent economic dynamic that would support the continued development of semiconductor manufacturing technology. Moore adopted a clearer, more direct metric for integrated circuit complexity than Knowles's package-pins: transistor count. Moore's 1965 observation was that at any given moment in the evolution of integrated circuit manufacturing technology, there was an optimal complexity point, as measured by the number of components on an integrated circuit, leading to a minimum manufacturing cost per component. Over time, with the development of technology, Moore argued, this optimal point would shift to both greater complexity and lower minimum manufacturing cost. Moore noted that the complexity of integrated circuits—as measured by the number of components per integrated circuit—had doubled every year between 1958 and 1965, with attending increases in performance. He argued that the technology and the economics involved would lead to a steady continuation of these trends for at least the following ten years.

The commonalities between Knowles's and Moore's arguments show the true context of Moore's 1965 publication of Moore's law: the attempt to communicate to broad technical audiences that integrated circuits were the future of electronics as a whole, by using arguments about cost and performance. Miniaturization's cost and performance possibilities were a notable focus of discussion among the advocates of silicon integrated circuits in the first half of the 1960s. While the commonalities between Knowles's and Moore's arguments are important in that they reveal this general concern, the differences between them are highly significant. Moore's idiom was far more successful than Knowles's. Moore crafted his argument into a clear and accessible presentation, grounded in the available data (however limited), with a direct, intuitive metric for integrated circuit complexity.

Thus, the immediate context of Moore's 1965 publication was a broad effort by semiconductor industry leaders to convince others that the future of electronics lay in integrated circuits. The 1964 IEEE session contributed greatly to this effort. The final speaker at the IEEE session—arguably one of the most powerful figures of the day in the industry—explicitly hailed integrated circuits as the future of electronics. He was Texas Instruments' president, Patrick Haggerty, and he too beat the drum of integrated circuits' cost advantage. He estimated that by 1973, integrated circuits would at the very least be cost competitive with all forms of conventional circuitry. More likely, Haggerty believed, was the dominance of integrated circuits by that time, priced at only one- to two-thirds the level of conventional circuits. However, Haggerty saw that this cost pressure for the conversion to integrated circuits would be counterbalanced by what he termed the "inertia lead-time factor." This delay in integrated circuit adoption, despite the cost imperative, would result from "[market] and tooling considerations, obsolescence, differences of opinion, human judgment, etc."[22] What Haggerty identified as the inertia lead-time factor was precisely the attitudinal orientation of electronics technologists that he and other leaders of the semiconductor industry attempted to change with their diverse arguments about the future of integrated circuits. They tried, as Moore would in the following year, to minimize the inertia lead-time factor.

MOORE'S VISION

Moore's chance to minimize the delay in the adoption of silicon integrated circuits came in January 1965, in the form of a letter. Lewis Young, the editor of the widely circulated trade journal *Electronics*, wrote to Moore on 28 January, inviting him to contribute to a special feature that the magazine was planning for its thirtieth anniversary issue in April 1965. "We are planning a feature that is tentatively called 'The Experts Look at the Future,'" he wrote, "and we are asking a half-dozen outstanding people to predict what is going to happen in their field of industry. Because of the innovations you have made in microelectronics and your close interest in this activity we ask you to write your opinion of the 'future for microelectronics'. . . . I think you might have fun doing this and I am sure the 65,000 readers of *Electronics* will find your comments stimulating and provocative."[23] To be sure, this brief article would be an excellent opportunity for Moore to convey his vision of the future for integrated circuits—a technology that his firm had pioneered and a market in which it was a strong leader. However, there was a drawback: "I need this material," Young stated, "here in New York by 1 March." Moore had, in essence, one month.

The following week, on 5 February, Moore sent his acceptance to Young. "I find the opportunity to predict the future in this area irresistible," Moore concluded, "and will, accordingly, be happy to prepare such a contribution."[24] Twenty-one days later, Moore sent his original manuscript to New York. In a cover letter to Young, Moore explained: "Enclosed is the manuscript for the article entitled, 'The Future of Integrated Electronics'. . . . I am taking the liberty of changing the title slightly from the one you suggested, since I think that 'integrated electronics' better describes the source for the advantages in this new technology than does the term 'microelectronics.'"[25]

Around the same time, on 1 March, Moore submitted this manuscript to the Patent Department of Fairchild Semiconductor, requesting permission to publish it. On the cover form for this request, Moore summarized his *Electronics* article as clearly as he drafted the complete piece: "The promise of integrated electronics is extrapolated into the wild blue yonder to show that there is still much to be done, but that integrated electronics will pervade all of electronics in the future. A curve is shown to suggest that the most economical way to make electronic systems in some ten years will be of the order of 65,000 components per integrated circuit." Addressing the Patent Department's true concern, Moore continued: "No proprietary data are included."[26]

ENDNOTES

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3. Moore, interviews with Thackray and Brock, 2001–2005; John Markoff, "It's Moore's Law, But Another Had the Idea First," *New York Times*, Section C, 18 April 2005.
4. For example, see the extended discussion by Douglas Engelbart in John Markoff, *What the Doormouse Said: How the 60s Counterculture Shaped the Personal Computer Industry* (New York: Viking, 2005).
5. Engelbart, oral history interview by Judy Adams and Henry Lowood, ed. Thierry Bardini, Stanford and the Silicon Valley Project, Stanford University. Available online at http://www.sul.stanford.edu/depts/hasrg/histsci/ssvoral/engelbart/engfmst1-ntb.html.
6. Engelbart, "Microelectronics and the Art of Similitude," *IEEE International Solid State Circuit Conference Digest of Technical Papers*, 3, (February 1960): 76.
7. Engelbart's embrace of similitude for microelectronics may have been due to the propinquity of one of its leading practitioners, Stephen J. Kline, a professor of mechanical engineering at Stanford. For more on similitude, see Kline's text on it from this era: Stephen J. Kline, *Similitude and Approximation Theory* (New York: McGraw-Hill, 1965).
8. Engelbart, "Microelectronics and the Art of Similitude," 77.
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10. R. Norman, J. Last, I. Haas, "Solid-State Micrologic Elements," *IEEE International Solid State Circuits Conference Digest of Technical Papers,* (3 February 1960): 83.
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13. C. Lester Hogan, "Types of Integrated Circuits," *IEEE Spectrum* 1:6, (June 1964): 63–71.
14. Robert N. Noyce, "Integrated Circuits in Military Equipment," *IEEE Spectrum* 1:6, (June 1964): 71–72.
15. Leonard C. Maier, "Integrated Circuits in Industrial Equipment," *IEEE Spectrum* 1:6, (June 1964): 72–75.
16. Ibid.
17. J. E. Brown, "Integrated Circuits in Consumer Products," *IEEE Spectrum* 1:6, (June 1964): 75.
18. C. Harry Knowles, "Research and Development in Integrated Circuits." *IEEE Spectrum* 1:6, (June 1964): 76–79.
19. Ibid.
20. Ibid.
21. Ibid.
22. Patrick E. Haggerty, "The Economic Impact of Integrated Circuitry" *IEEE Spectrum* 1:6, (June 1964): 80–82.
23. Young to Moore, photocopy of original letter, (30 January1965), Moore's personal papers.
24. Moore to Young, photocopy of original letter, (5 February 1965), Moore's personal papers.
25. Moore to Young, photocopy of original letter, (26 February 1965), Moore's personal papers.
26. Photocopy of original document, dated 1 March 1965, Moore's personal papers.

THE FUTURE OF INTEGRATED ELECTRONICS

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If allowed the luxury of a broad definition of *integrated electronics* to include all the various technologies which are referred to as microelectronics today, as well as any additional ones which result in electronics functions supplied to the user as irreducible units, then the future of integrated electronics is the future of electronics itself. Only a few areas in the realm of electronics do not obviously benefit from the advantages that can be expected from integration.

This paper examines the driving force which will result in integrated functions pervading the electronics art and broaden its scope beyond my imagination. Its purpose, however, is not to anticipate these extended applications, but rather to predict the development of integrated electronics technology for perhaps the next ten years. If one subscribes to the theory of the increasing rate of technical evolution, even such a relatively modest objective is almost certain to result in gross errors.

The origin of integrated electronics probably occurred someplace in the latter part of the last decade with the original objective dictated by the need implied in the term microelectronics. The developing desire to include increasingly complex electronic functions in limited space and with minimum possible weight was the initial motivation. Several approaches to the realization of these objectives evolved, including microassembly techniques for individual components, as well as thin-film structures and semiconductor integrated circuits.

The various technologies have evolved rapidly and convergently. Many people involved in integrated electronics today believe that eventually a combination of the various approaches taking maximum advantage of each for a particular application will be the way of the future. The advocates of semiconductor integrated circuitry are taking advantage of the improved characteristics of thin-film resistors by applying such films directly to an active semiconductor substrate, while those advocating a technology based upon films are developing sophisticated techniques for the attachment of active semiconductor devices to the passive film arrays. Both approaches have worked well and are being used in equipment today.

At present, integrated electronics is an established technique. Most companies in the components business are working with at least one of the several approaches. For new military systems the incorporation of integrated electronics is almost mandatory. In fact, the reliability, size and weight required by some of the systems is achievable only with integration. Such programs as Apollo have demonstrated the reliability of integrated electronics by showing that complete circuit functions are as free from failure as had previously been established for the highest quality individual transistors. Most companies in the commercial computer field have machines employing integrated electronics either in design or in early production. There is little question that these machines will offer advantages in cost and performance over those which can be built using "conventional" electronics. Instruments of various sorts, especially the rapidly increasing array of instruments employing digital techniques, are starting to use integrated electronics, where the advantages of decreased cost, both in manufacture and design, are the principal motivations.

The use of linear integrated circuitry is still restricted primarily to the military, since such integrated functions are still relatively expensive and not available in the considerable variety required if a major fraction of linear electronics is to be integrated. However, first examples of the use of linear integrated circuits are being seen in commercial electronics, particularly where low frequency amplifiers offering the benefits of small size must be employed.

In any case, integrated electronics have demonstrated high reliability. Even at their present low level of production relative to individual components, they offer reduced systems cost. In many instances improved performance is realized. Thus a foundation has been constructed for integrated electronics to continue to pervade all of electronics. Their major impact will be to make electronic techniques more generally available throughout all of society, making available many functions that presently are done inadequately by other techniques or not done at all. The principal advantages which will result in this expansion are lower costs and the greatly simplified design of systems which comes from a readily available supply of low cost functional packages.

Such advantages can be expected to result in the proliferation of electronics. The individual might see the fruits of integrated electronics in such manifestations as home computers, or at least terminals connected to a central computer, automatic controls for automobiles, or portable communications equipment. The electronic wrist watch lacks only a display to be feasible now. But the principal benefactors of the technology will be the makers of large systems. For example, the telephone communications networks can make extensive use of integrated electronics not only in switching and data processing but by employing integrated digital filters for the separation of channels on multiplex equipment. The computer industry in general will benefit. In addition to being able to make machines similar to those in existence today at lower cost and with faster turnaround, it will be possible to make much more powerful computers perhaps organized in completely new ways. For example, the distribution of memory throughout the electronics will become a practical approach. In addition, the resulting improved reliability allows the construction of larger processing units, although the reliability problems associated with the electromechanical input-output equipment might require different solutions.

Not only will the logic portion of computers benefit from the technology of integrated electronics, but other portions as well.

Already, the use of active flip-flop storage for buffer registers is widespread because of the requirements for memory speeds compatible with ever increasing logic rates. Integrated electronics can be expected to expand the range of memory size in which it is advantageous to use flip-flop storage from a speed-cost point of view. The area of random access memory presently supplied by thin films ~~of~~ or magnetic cores can expect active semiconductor memories to begin to compete on a cost basis, first for small, fast memories, possibly more broadly later. Of course, other competing technologies such as ferrite plates, permalloy sheets, and woven wire also show promise of competing with cores. In any case, the peripheral electronics associated with memories will be simplified and reduced in cost by integration.

Next, consider what form the evolution might take and some of the specific accomplishments that might be extrapolated.

The only reasonable candidates presently in existence for the active elements are semiconductor devices. For most applications, where precision of passive elements is not the prime requisite, lowest cost and highest reliability look achievable through the use of semiconductor passive elements as well. Hence, for the major fraction of applications the general technology of semiconductor integrated circuits will continue to predominate. In fact, silicon will likely remain the basic material although others will be of use in specific applications. For example, gallium arsenide will be important in integrated microwave functions. Silicon will predominate at lower frequencies because of the technology which has evolved around it and its oxide. In addition silicon is an abundant and relatively inexpensive starting material.

The cost advantage of integrated structures continues to increase as the technology evolves toward the production of larger and larger circuit functions on a single semiconductor substrate. Figure 1 shows a plot of relative costs per component in an integrated function versus the number of components per integrated circuit for 1962, 1965 and estimated for 1970. Obviously such a curve can only be qualitative, since the actual cost is, of necessity, a strong function of the specific circuit specifications. In this log-log plot at relatively low complexity the cost per component is nearly inversely proportional to the number of components per circuit. This is the direct result of the equivalent piece of semiconductor in the equivalent package containing more components. As complexity increases, at any given point in the evolution of the technology a minimum cost per component is reached, beyond which decreased yields more than compensate for the increased complexity. This minimum in cost per component at the present time is estimated to be in the vicinity of 50 components per circuit. The minimum is moving rapidly toward greater complexity while the entire curve is falling. The bottom curve suggests that in five years the minimum cost per component might be expected in circuits with the order of 1,000 components per circuit, providing such circuit functions can be found that they can be produced in moderate quantites. At such time the manufacturing cost per component can be expected to be at least an order of magnitude lower than it is at present.

Figure 2 shows an extrapolation of the circuit complexity corresponding to the minimum cost per component. The first point on this plot corresponds to the manufacturing of the first planar silicon transistor, which can be considered a starting point for the present semiconductor integrated technology. The complexity for minimum component costs has increased at a rate of roughly a factor of two per year. Certainly over the near term this rate can be expected to continue, if not to increase. The longer term extrapolation is a bit more nebulous, although there is no obvious reason for stopping the curve before it intersects the top of the graph. This curve was purposely plotted with a rather obscure unit as the ordinate so that the logic of the extrapolation of the historical data might be appreciated without the confusion of the absolute numbers implied. In fact, the top corresponds to about 65,000 components per integrated circuit. One must question the reasonableness of an integrated array of this complexity.

First, even neglecting yield, can so large a circuit be made upon a single wafer?

With the dimensional tolerances already being employed in integrated circuits, it is readily possible to make completely isolated, high performance, transistors on two mil centers. Such a two mil square can also contain several kilohms of resistance or a few diodes. This allows at least 500 components per linear inch or a quarter million per square inch. Thus, 65,000 components need only occupy an area of the order of one-half inch square. On the present silicon wafers usually an inch or more in diameter, there is ample room for such a structure, providing the components can be closely packed and no space wasted for interconnection patterns. This is realistic since a strong trend toward multilayer metallization patterns separated by dielectric films is already evident in order to achieve a level of complexity above the presently available integrated circuits. It is worth noting that this density of components can be achieved by present optical techniques and does not require the more exotic electron beam operations which are being studied for the possibility of making even smaller structures.

Second, is any reasonable extrapolation of present capability compatible with such complexity?

While to those of us in the semiconductor industry it sometimes seems difficult to realize, there is no fundamental reason why the device yields are limited below 100%. Nothing comparable to the thermodynamic equilibrium considerations which often limit yields in chemical reactions exists. Device yields can be raised as high as is economically justified. It is not even necessary that any fundamental information be collected or that present processes be replaced by new processes. It is only necessary that the required engineering effort be committed. At present with respect to individual devices, however, packaging costs generally exceed considerably the cost of the semiconductor structure itself. Thus there is no real incentive to improve the yield of devices on the semiconductor wafer. In the early days of integrated circuitry, the state of sophistication of the processing which had developed for individual components was not sufficient to make the analogous situation true for the integrated structures. Yields on integrated circuits were extremely low. Thus incentive existed to improve the processes. Today ordinary integrated circuits are made with yields comparable with those obtained for individual semiconductor devices. Similar evolution will occur, if necessary, to make larger arrays economical to produce, if such arrays are desirable from other considerations.

Third, is it possible to remove the heat generated by such a function?

By taking a standard, high-speed digital computer and shrinking the volume of the system down to that required for the components themselves, it is easy to show that with the present power dissipations, the resultant mass should glow brightly. In fact, this is not a realistic transformation. In the first place, integrated electronic structures are two-dimensional rather than three-dimensional, leaving a surface available for cooling close to each center of heat generation. Secondly, power is needed primarily to drive the various lines and capacitances associated with the system. As long as a function is confined to a small area on a wafer, the amount of impedance which must be driven is distinctly limited. In fact, it can be shown that shrinking the dimensions on an integrated structure results in the possibility of operating it at higher speed for the same power per unit area. At power densities well below those at which many transistors operate today, one can operate integrated functions at speeds in excesses of those in any systems presently in existence.

Even if such large functions can be made, it is necessary to ask under what circumstances is it reasonable that they be made. In order for it to be reasonable, the total cost of making a particular system function must be minimized. This implies either amortizing the engineering over several identical items, or that flexible techniques be evolved for doing the engineering of large functions so that no disproportionate expense need be borne by a particular array. Perhaps design automation procedures are possible to translate from logic diagram to the technological realization requiring little special engineering.

It may prove to be economically more reasonable to build large systems out of smaller functions with packaging and interconnection techniques supplying the necessary flexibility. The availability of large functions combined with the possibility of functional design and construction should have a very significant impact on the manufacturer of large systems, allowing him to design and construct a wide variety of equipment rapidly and economically.

As far as the technologies for achieving large functions is concerned, several possibilities exist, any one of which is capable of being developed to the point that these arrays are feasible. It is not clear if one of these will dominate or if a combination will be employed.

One possibility is to continue to require that every component in an array be good in order for the array to be acceptable. Such an approach puts maximum reliance on the processing.

An alternative is to test smaller subunits destined to be connected in the integrated function, selecting those smaller units which are good, then to design a specific interconnection pattern to employ only the good structures in the function intraconnection level. This technique of making a special pattern for each semiconductor wafer, depending upon the pattern of good structures, is being investigated presently in several laboratories. It implies a degree of interconnection flexibility which might also solve the problem of production of small quantitites of special arrays economically, since the flexible interconnection procedures required to avoid bad units should also allow automatic design of various functions.

Other schemes for including redundancy have been suggested. Some involve the use of external logic to avoid bad regions, while others operate on the internal organs of the integrated array itself. In any case such arrays will be achieved. It only remains to see if redundancy will prove useful or not.

While the revolutionary changes integration can be expected to impart upon digital systems cannot be expected throughout linear electronics, a considerable degree of integration will be achieved. The lack of large capacitors and inductors is the greatest fundamental limitation on integrated microelectronics in the linear area. By their very nature, such elements require the storage of energy in a volume. For high Q it is necessary that the volume be large. The incompatibility of large volume and microelectronics is obvious from the terms themselves. Certain resonance phenomena, such as those in piezoelectric crystals, can be expected to have some application for tuning functions, although inductors and capacitors will be with us for some time. The integrated rf amplifier of the future might well consist of integrated stages of gain, giving high performance at minimum cost, interspersed with relatively large tuning elements.

Other linear functions will benefit considerably. The matching and tracking of similar components in integrated structures will allow the design of differential amplifiers of greatly improved performance. The use of thermal feedback effects to temperature stabilize integrated structures to a small fraction of a degree will allow the construction of oscillators with crystal stability.

Even in the microwave area structures included in the definition of integrated electronics will become increasingly important.

The ability to make and assemble components small compared with the wavelengths involved will allow the use of lumped parameter design, at least at the lower frequencies. It is difficult to predict at the present time just how extensive the invasion of the microwave area by integrated electronics will be. The successful realization of such items as phased-array antennas using a multiplicity of integrated microwave power sources could completely revolutionize radar. Such a system is a distinct possibility.

In summary, integrated electronics will allow the advantages of electronics to be applied generally throughout society. While the principal impact will be on digital equipment and will result in much broader use of digital circuit techniques, all of electronics will be strongly effected. There remain many significant problems for the electronics industry to solve in attempting to take advantage of this evolving technology to supply the rapidly increasing electronic requirements of the world.

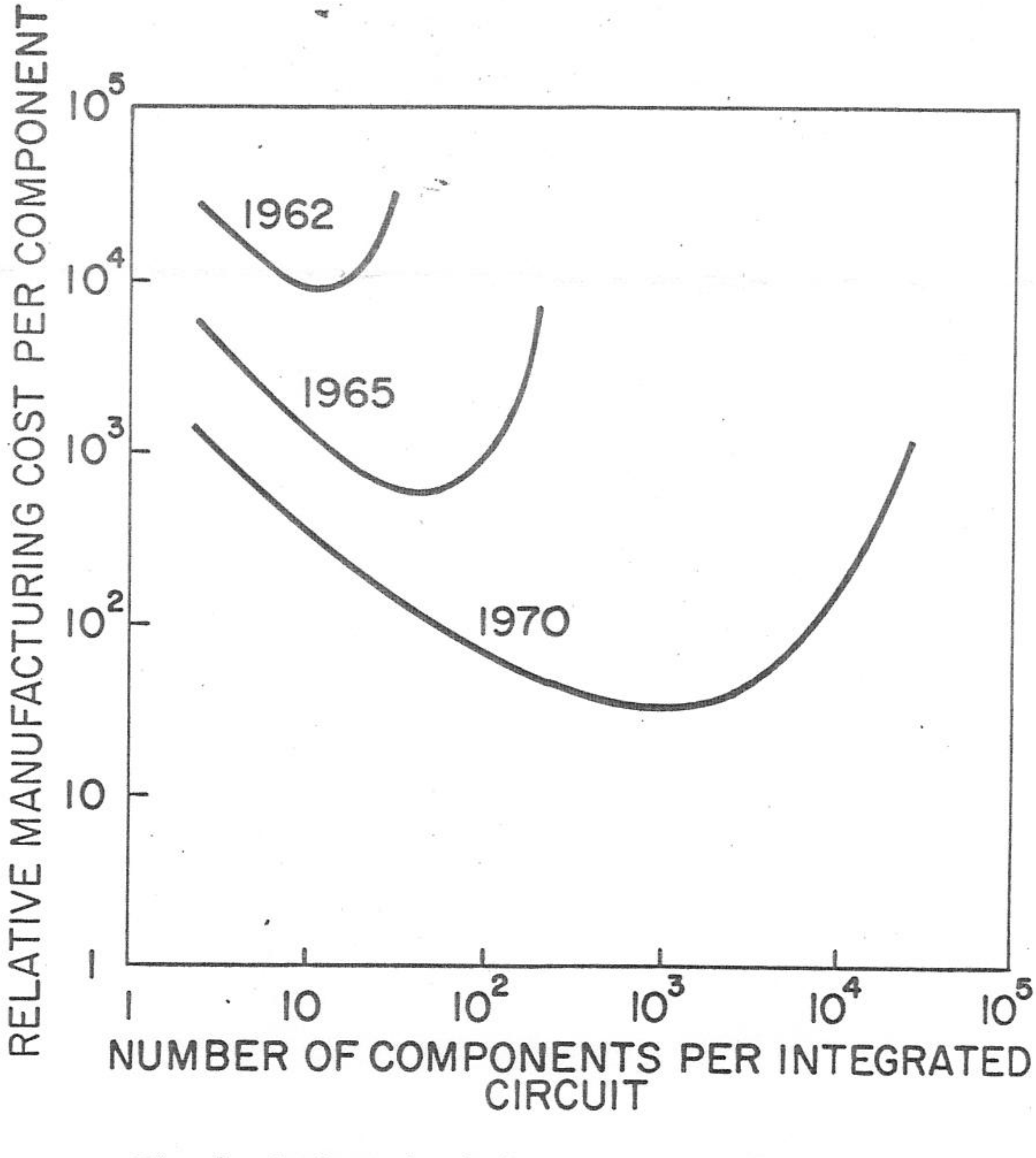

Fig. 1 Estimated relative cost per component vs complexity for a typical integrated function for three different times.

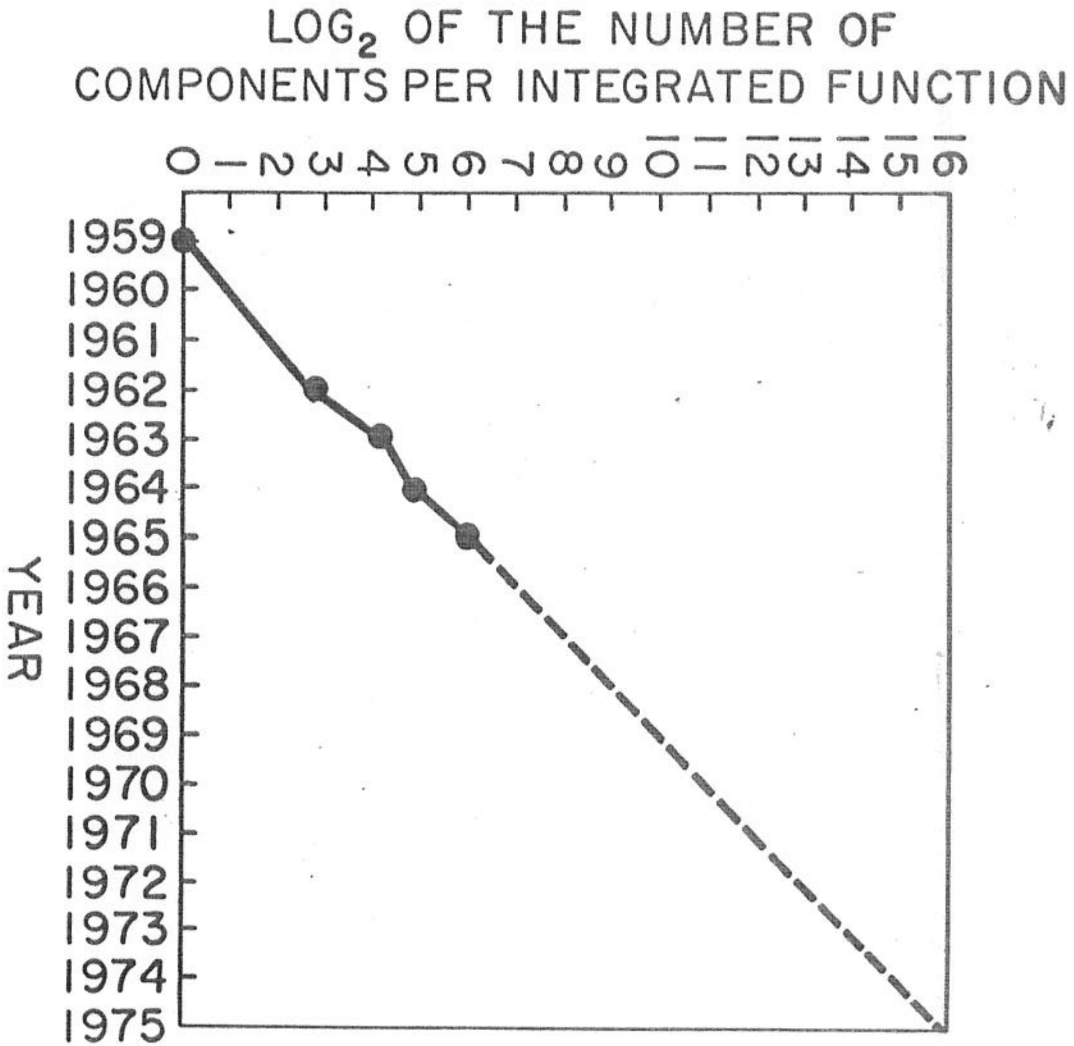

Fig. 2 Number of components per integrated function for minimum cost per component extrapolated vs time.

BIOGRAPHICAL SKETCH

GORDON E. MOORE received his B. S. degree in Chemistry, University of California and his Ph. D. in Physical Chemistry, California Institute of Technology, Pasadena, California. With the Applied Physics Laboratory of Johns-Hopkins University, then Shockley Semiconductor Laboratory; one of the founders of Fairchild Semiconductor and since 1959 has been Director of the Research and Development Laboratories of Fairchild.

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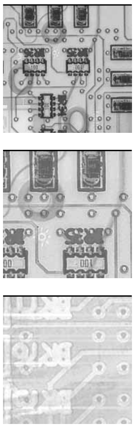

CHAPTER 5

Cramming More Components Onto Integrated Circuits

Gordon E. Moore

The future of integrated electronics is the future of electronics itself. The advantages of integration will bring about a proliferation of electronics, pushing this science into many new areas.

Integrated circuits will lead to such wonders as home computers—or at least terminals connected to a central computer—automatic controls for automobiles, and personal portable communications equipment. The electronic wristwatch needs only a display to be feasible today.

But the biggest potential lies in the production of large systems. In telephone communications, integrated circuits in digital filters will separate channels on multiplex equipment. Integrated circuits will also switch telephone circuits and perform data processing.

Computers will be more powerful and will be organized in completely different ways. For example, memories built of integrated electronics may be distributed throughout the machine instead of being concentrated in a central unit. In addition, the improved reliability made possible by integrated circuits will allow the construction of larger processing units. Machines similar to those in existence today will be built at lower costs and with faster turnaround.

PRESENT AND FUTURE

By integrated electronics, I mean all the various technologies that are referred to as microelectronics today, as well as any additional ones that result in electronics func-

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Gordon E. Moore, "Cramming More Components Onto Integrated Circuits." Reprinted, with permission, from *Electronics* 38:8, (19 April 1965), 114–117.

tions supplied to the user as irreducible units. These technologies were first investigated in the late 1950s. The object was to miniaturize electronics equipment to include increasingly complex electronic functions in limited space with minimum weight. Several approaches evolved, including microassembly techniques for individual components, thin-film structures, and semiconductor integrated circuits.

Each approach evolved rapidly and converged so that each borrowed techniques from another. Many researchers believe the way of the future to be a combination of the various approaches.

The advocates of semiconductor integrated circuitry are already using the improved characteristics of thin-film resistors by applying such films directly to an active semiconductor substrate. Those advocating a technology based upon films are developing sophisticated techniques for the attachment of active semiconductor devices to the passive film arrays.

Both approaches have worked well and are being used in equipment today.

THE ESTABLISHMENT

Integrated electronics is established today. Its techniques are almost mandatory for new military systems, since the reliability, size, and weight required by some of them is achievable only with integration. Such programs as Apollo, for manned moon flight, have demonstrated the reliability of integrated electronics by showing that complete circuit functions are as free from failure as the best individual transistors.

Most companies in the commercial computer field have machines in design or in early production employing integrated electronics. These machines cost less and perform better than those that use “conventional” electronics.

Instruments of various sorts, especially the rapidly increasing numbers employing digital techniques, are starting to use integration because it cuts costs of both manufacture and design.

The use of linear integrated circuitry is still restricted primarily to the military. Such integrated functions are expensive and not available in the variety required to satisfy a major fraction of linear electronics. But the first applications are beginning to appear in commercial electronics, particularly in equipment that needs low-frequency amplifiers of small size.

RELIABILITY COUNTS

In almost every case, integrated electronics has demonstrated high reliability. Even at the present level of production—low compared to that of discrete components—it offers reduced systems cost, and in many systems improved performance has been realized.

Integrated electronics will make electronic techniques more generally available throughout all of society, performing many functions that presently are done inadequately by other techniques or not done at all. The principal advantages will be lower costs and greatly simplified design—payoffs from a ready supply of low-cost functional packages.

For most applications, semiconductor integrated circuits will predominate. Semiconductor devices are the only reasonable candidates presently in existence for the active elements of integrated circuits. Passive semiconductor elements look attractive, too, because of their potential for low cost and high reliability, but they can be used only if precision is not a prime requisite.

Silicon is likely to remain the basic material, although others will be of use in specific applications. For example, gallium arsenide will be important in integrated microwave functions. But silicon will predominate at lower frequencies because of the technology that has already evolved around it and its oxide and because it is an abundant and relatively inexpensive starting material.

COSTS AND CURVES

Reduced cost is one of the big attractions of integrated electronics, and the cost advantage continues to increase as the technology evolves toward the production of larger and larger circuit functions on a single semiconductor substrate. For simple circuits, the cost per component is nearly inversely proportional to the number of components, the result of the equivalent piece of semiconductor in the equivalent package containing more components. But as components are added, decreased yields more than compensate for the increased complexity, tending to raise the cost per component. Thus there is a minimum cost at any given time in the evolution of the technology. At present, it is reached when 50 components are used per circuit. But the minimum is rising rapidly while the entire cost curve is falling (see Figure 1). If we look ahead five years, a plot of costs suggests that the minimum cost per component might be expected in circuits with about 1,000 components per circuit (providing such circuit functions can be produced in moderate quantities.) In 1970, the manufacturing cost per component can be expected to be only a tenth of the present cost.

The complexity for minimum component costs has increased at a rate of roughly a factor of two per year (see Figure 2). Certainly over the short term this rate can be expected to continue, if not to increase. Over the longer term, the rate of increase is a bit more uncertain, although there is no reason to believe it will not remain nearly constant for at least ten years. That means by 1975, the number of components per integrated circuit for minimum cost will be 65,000.

I believe that such a large circuit can be built on a single wafer.

TWO-MIL SQUARES

With the dimensional tolerances already being employed in integrated circuits, isolated high-performance transistors can be built on centers two thousandths of an inch apart. Such a two-mil square can also contain several kilohms of resistance or a few diodes. This allows at least 500 components per linear inch or a quarter million per square inch. Thus, 65,000 components need occupy only about one-fourth a square inch.

On the silicon wafer currently used, usually an inch or more in diameter, there is ample room for such a structure if the components can be closely packed with no space wasted for interconnection patterns. This is realistic, since efforts to achieve a level of complexity above the presently available integrated circuits are already underway using multilayer metallization patterns separated by dielectric films. Such a density of components can be achieved by present optical techniques and does not require

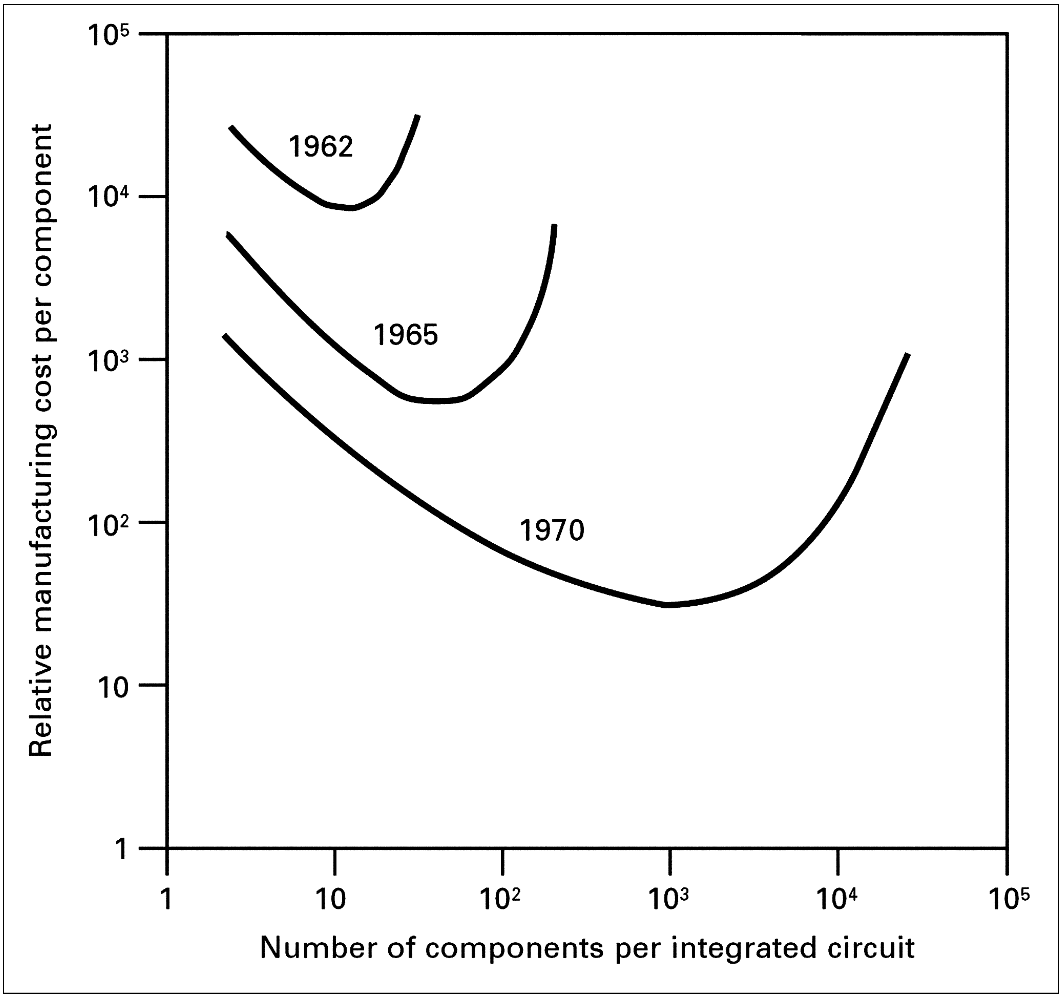


FIGURE 1.

the more exotic techniques, such as electron beam operations, which are being studied to make even smaller structures.

INCREASING THE YIELD

There is no fundamental obstacle to achieving device yields of 100 percent. At present, packaging costs so far exceed the cost of the semiconductor structure itself that there is no incentive to improve yields, but they can be raised as high as is economically justified. No barrier exists comparable to the thermodynamic equilibrium considerations that often limit yields in chemical reactions; it is not even necessary to do any fundamental research or to replace present processes. Only the engineering effort is needed.

In the early days of integrated circuitry, when yields were extremely low, there was such incentive. Today ordinary integrated circuits are made with yields comparable

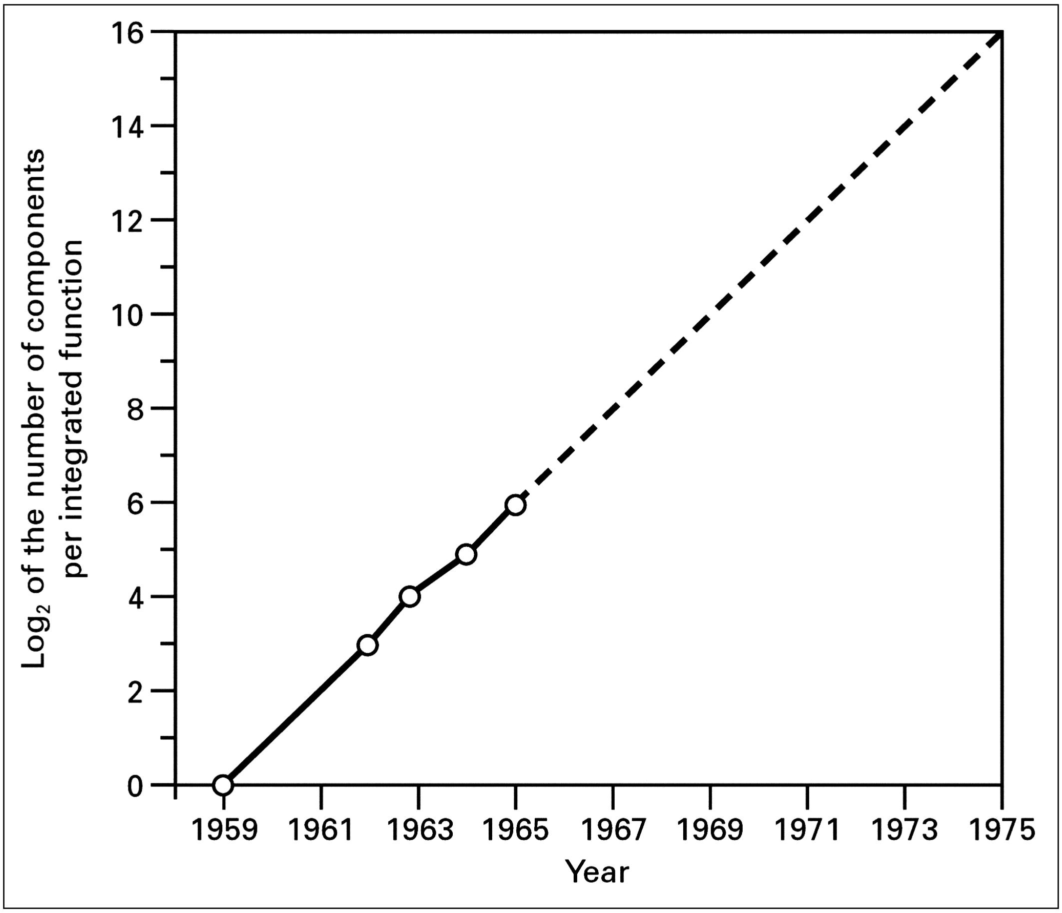


FIGURE 2.

with those obtained for individual semiconductor devices. The same pattern will make larger arrays economical, if other considerations make such arrays desirable.

Heat Problem

Will it be possible to remove the heat generated by tens of thousands of components in a single silicon chip?

If we could shrink the volume of a standard high-speed digital computer to that required for the components themselves, we would expect it to glow brightly with present power dissipation. But it won't happen with integrated circuits. Since integrated electronic structures are two-dimensional, they have a surface available for cooling close to each center of heat generation. In addition, power is needed primarily to drive the various lines and capacitances associated with the system. As long as a function is confined to a small area on a wafer, the amount of capacitance that must be driven is distinctly limited. In fact, shrinking dimensions on an integrated structure makes it possible to operate the structure at higher speed for the same power per unit area.

DAY OF RECKONING

Clearly, we will be able to build such component-crammed equipment. Next, we ask under what circumstances we should do it. The total cost of making a particular system function must be minimized. To do so, we could amortize the engineering over several identical items or evolve flexible techniques for the engineering of large functions so that no disproportionate expense need be borne by a particular array. Perhaps newly devised design automation procedures could translate from logic diagram to technological realization without any special engineering.

It may prove to be more economical to build large systems out of smaller functions, which are separately packaged and interconnected. The availability of large functions, combined with functional design and construction, should allow the manufacturer of large systems to design and construct a considerable variety of equipment both rapidly and economically.

LINEAR CIRCUITRY

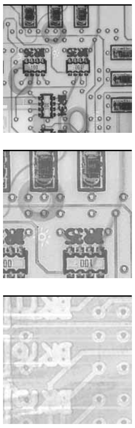
Integration will not change linear systems as radically as digital systems. Still, a considerable degree of integration will be achieved with linear circuits. The lack of large-value capacitors and inductors is the greatest fundamental limitation to integrated electronics in the linear area.

By their very nature, such elements require the storage of energy in a volume. For high Q it is necessary that the volume be large. The incompatibility of large volume and integrated electronics is obvious from the terms themselves. Certain resonance phenomena, such as those in piezoelectric crystals, can be expected to have some applications for tuning functions, but inductors and capacitors will be with us for some time.

The integrated r-f amplifier of the future might well consist of integrated stages of gain, giving high performance at minimum cost, interspersed with relatively large tuning elements.

Other linear functions will be changed considerably. The matching and tracking of similar components in integrated structures will allow the design of differential amplifiers of greatly improved performance. The use of thermal feedback effects to stabilize integrated structures to a small fraction of a degree will allow the construction of oscillators with crystal stability.

Even in the microwave area, structures included in the definition of integrated electronics will become increasingly important. The ability to make and assemble components small compared with the wavelengths involved will allow the use of lumped parameter design, at least at the lower frequencies. It is difficult to predict at the present time just how extensive the invasion of the microwave area by integrated electronics will be. The successful realization of such items as phased-array antennas, for example, using a multiplicity of integrated microwave power sources could completely revolutionize radar.



CHAPTER 6

PROGRESS IN DIGITAL INTEGRATED ELECTRONICS

Gordon E. Moore

Complexity of integrated circuits has approximately doubled every year since their introduction. Cost per function has decreased several thousandfold, while system performance and reliability have been improved dramatically. Many aspects of processing and design technology have contributed to make the manufacture of such functions as complex single chip microprocessors or memory circuits economically feasible. It is possible to analyze the increase in complexity plotted in Figure 1 into different factors that can, in turn, be examined to see what contributions have been important in this development and how they might be expected to continue to evolve. The expected trends can be recombined to see how long exponential growth in complexity can be expected to continue.

A first factor is the area of the integrated structures. Chip areas for some of the largest of the circuits used in constructing Figure 1 are plotted in Figure 2. Here again, the trend follows an exponential quite well, but with significantly lower slope than the complexity curve. Chip area for maximum complexity has increased by a factor of approximately 20 from the first planar transistor in 1959 to the 16,384-bit charge-coupled device memory chip that corresponds to the point plotted for 1975, while complexity, according to the annual doubling law, should have increased about 65,000-fold. Clearly much of the increased complexity had to result from higher density of components on the chip, rather than from the increased area available through the use of larger chips.

Gordon E. Moore, “Progress in Digital Integrated Electronics.” © 1975 IEEE. Reprinted, with permission, from *Technical Digest*, IEEE International Electron Devices Meeting 21, (1975): 11–13.

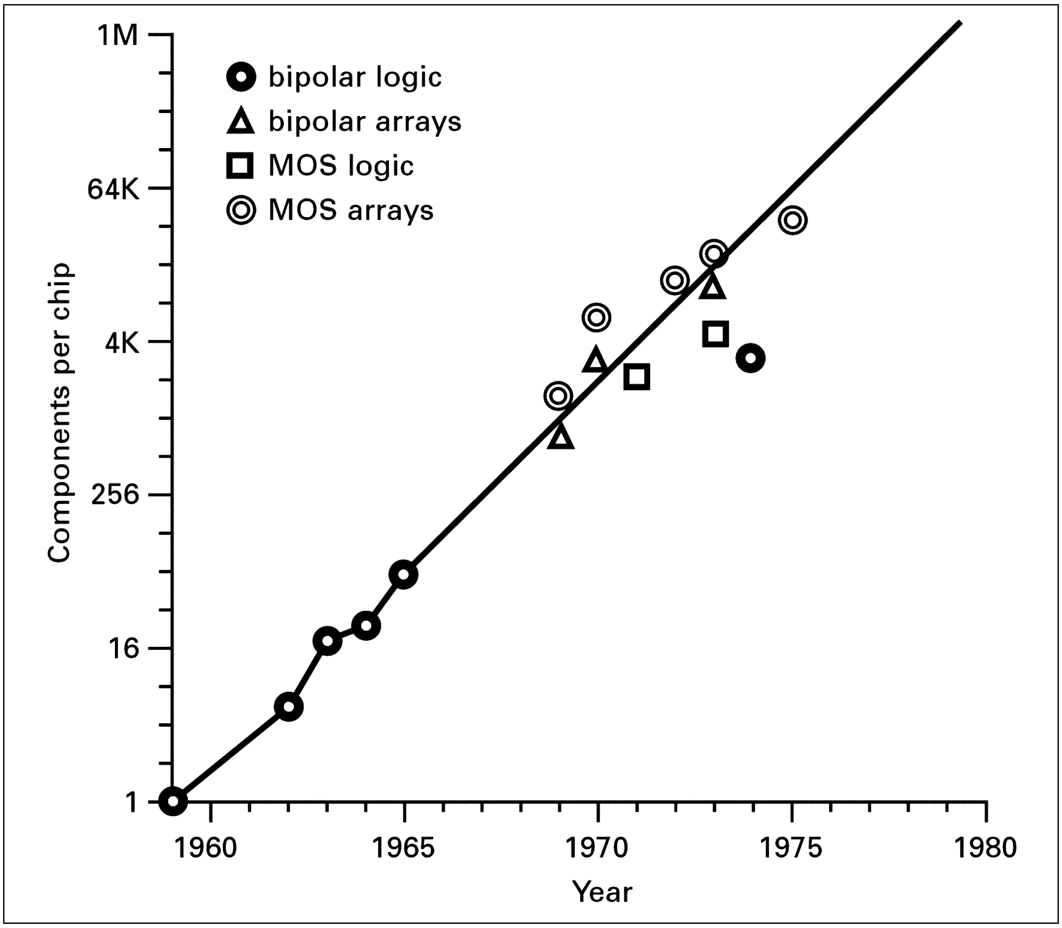


FIGURE 1. Approximate component count for complex integrated circuits vs. year of introduction.

Density was increased partially by using finer scale microstructures. The first integrated circuits of 1961 used line widths of 1 mil (≅25 micrometers) while the 1975 device uses 5 micrometer lines. Both line width and spacing between lines are equally important in improving density. Since they have not always been equal, the average of the two is a good parameter to relate to the area that a structure might occupy. Density can be expected to be proportional to the reciprocal of area, so the contribution to improve density vs. time from the use of smaller dimensions is plotted in Figure 3.

Neglecting the first planar transistor, where very conservative line width and spacing was employed, there is again a reasonable fit to an exponential growth. From the exponential approximation represented by the straight line in Figure 3, the increase in density from this source over the 1959–1975 period is a factor of approximately 32.

Combining the contribution of larger chip area and higher density resulting from geometry accounts for a 640-fold increase in complexity, leaving a factor of about 100 to account for through 1975, as is shown graphically in Figure 4. This factor is the contribution of circuit and device advances to higher density. It is noteworthy that this

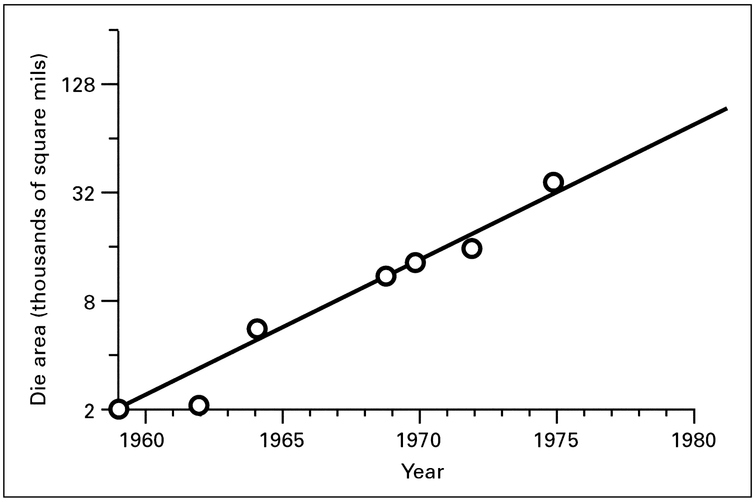


FIGURE 2. Increase in die area for most complex integrated devices commercially available.

contribution to complexity has been more important than either increased chip area or finer lines. Increasingly the surface areas of the integrated devices have been committed to components rather than to such inactive structures as device isolation and interconnections, and the components themselves have trended toward minimum size, consistent with the dimensional tolerances employed.

Can these Trends Continue?

Extrapolating the curve for die size to 1980 suggests that chip area might be about 90,000 sq. mils, or the equivalent of 0.3 inches square. Such a die size is clearly consistent with the 3-inch wafer presently widely used by the industry. In fact, the size of the wafers themselves has grown about as fast as has die size during the time period under consideration and can be expected to continue to grow. Extension to larger die size depends principally upon the continued reduction in the density of defects. Since the existence of the type of defects that harm integrated circuits is not fundamental, their density can be reduced as long as such reduction has sufficient economic merit to justify the effort. I see sufficient continued merit to expect progress to continue for the next

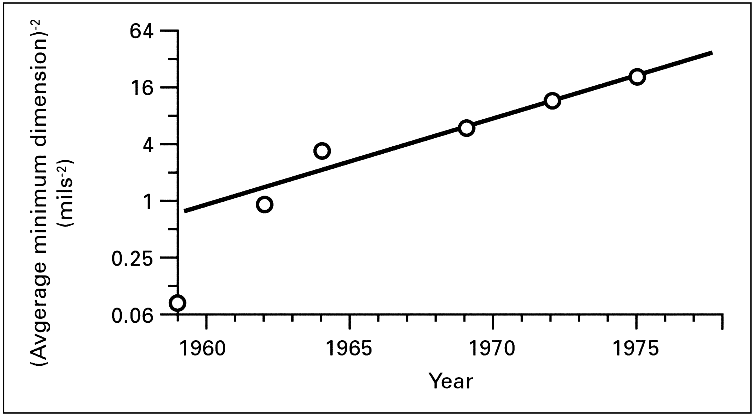


FIGURE 3. Device density contribution from the decrease in line widths and spacings.

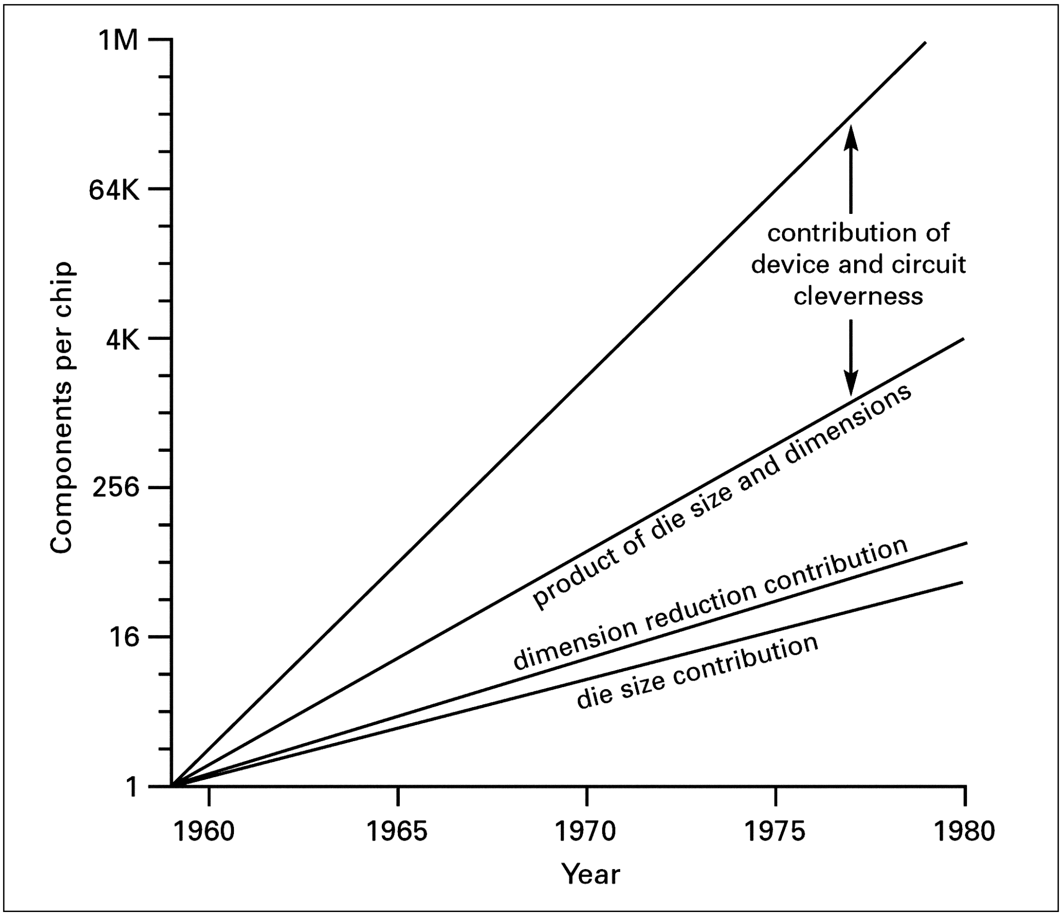


Figure 4. Decomposition of the complexity curve into various components.

several years. Accordingly, there is no present reason to expect a change in the trend shown in Figure 2.

With respect to dimensions, in these complex devices we are still far from the minimum device sizes limited by such fundamental considerations as the charge on the electron or the atomic structure of matter. Discrete devices with submicrometer dimensions show that no basic problems should be expected at least until the average line width and spaces are a micrometer or less. This allows for an additional factor of improvement at least equal to the contribution from the finer geometries of the last fifteen years. Work in nonoptical masking techniques, both electron beam and X-ray, suggests that the required resolution capabilities will be available. Much work is required to be sure that defect densities continue to improve as devices are scaled to take advantage of the improved resolution. However, I see no reason to expect the rate of progress in the use of smaller minimum dimensions in complex circuits to decrease in the near future. This contribution should continue along the curve of Figure 3.

With respect to the factor contributed by device and circuit cleverness, however, the situation is different. Here we are approaching a limit that must slow the rate of

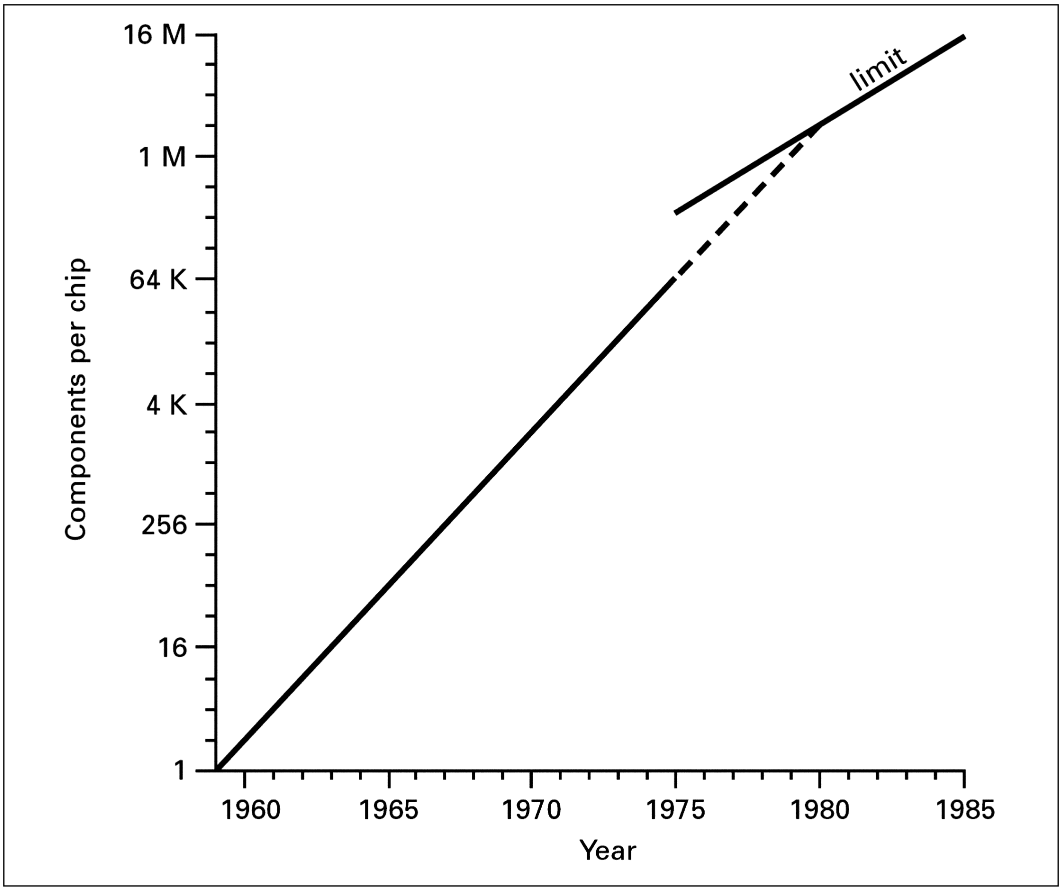
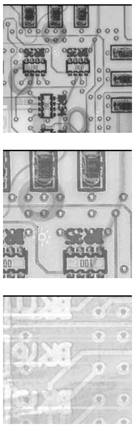


FIGURE 5. Projection of the complexity curve reflecting the limit on increased density through invention.

progress. The CCD structure can approach closely the maximum density practical. This structure requires no contacts to the components within the array, but uses gate electrodes that can be at minimum spacing to transfer charge and information from one location to the next. Some improvement in overall packing efficiency is possible beyond the structure plotted as the 1975 point in Figure 1, but it is unlikely that the packing efficiency alone can contribute as much as a factor of four, and this only in serial data paths. Accordingly, I am inclined to suggest a limit to the contribution of circuit and device cleverness of another factor of four in component density.

With this factor disappearing as an important contributor, the rate of increase of complexity can be expected to change slope in the next few years as shown in Figure 5. The new slope might approximate a doubling every two years, rather than every year, by the end of the decade.

Even at this reduced slope, integrated structures containing several million components can be expected within ten years. These new devices will continue to reduce the cost of electronic functions and extend the utility of digital electronics more broadly throughout society.



CHAPTER 7

Moore's Law at 40

Gordon E. Moore

Following a paper that I wrote in 1965 and a speech that I gave in 1975, the term "Moore's law" was coined as a name for a type of prediction that I had made. Over time, the term was used much more broadly, referring to almost any phenomenon related to the semiconductor industry that when plotted on semilog graph paper approximates a straight line. In more recent years, Moore's law has been connected to nearly any exponential change in technology. I hesitate to focus on the history of my predictions, for by so doing I might restrict the definition of Moore's law. Nevertheless, in my discussion, I will review the background to my predictions, the reasoning behind them, how these predictions aligned with actual industry performance, and why they did. I will close with a look forward at the future prospects for the prediction.

Overview

Moore's law is really about economics. My prediction was about the future direction of the semiconductor industry, and I have found that the industry is best understood through some of its underlying economics. To form an overall view of the industry, it is useful to consider a plot of revenue versus time. As Figure 1 indicates, the semiconductor industry has been a strong growth industry: it has grown a hundredfold during Intel's existence. However, from my point of view, this plot of revenue growth really underestimates the true rate of growth for the industry.

I prefer a manufacturing viewpoint, analyzing the industry from the perspective of the products we have made. I started with this approach several years ago, looking at the worldwide production of all semiconductor devices, estimating the number of transistors in these devices, and looking at the growth in the total number of transistors shipped in working electronic devices (Figure 2).

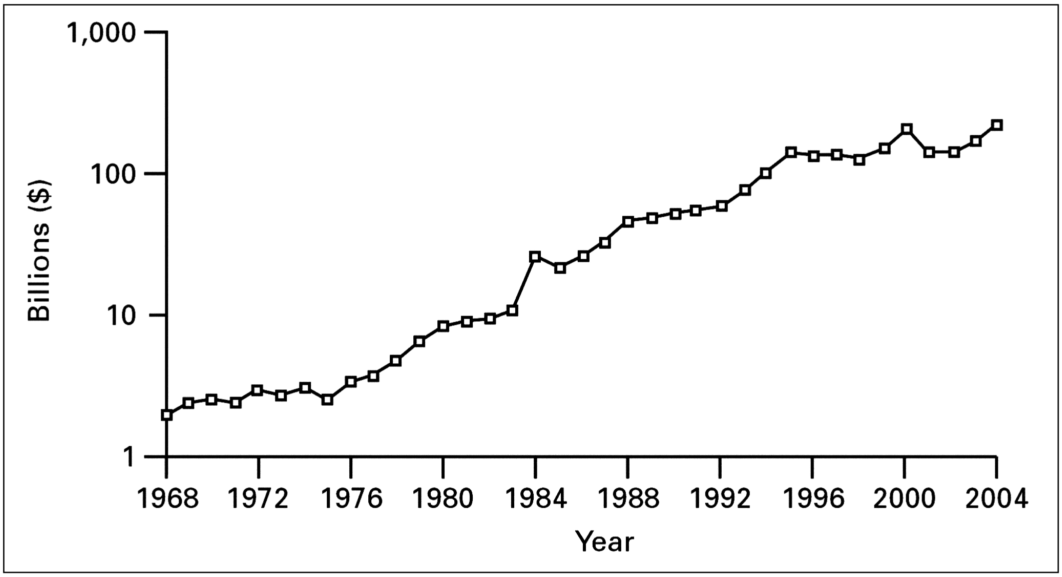


FIGURE 1. Global semiconductor industry revenues (1968–2004). Source: Intel/WSTS, May 2005.

This is *rapid* growth! In fact, there was even a period during the 1970s when the industry was *more than doubling* the total number of transistors ever made every year, so that more electronics were built each year than existed at the beginning of the year. The pace has slowed recently but is still on a good growth curve. Interestingly, there are no bumps and wiggles in this transistor output curve (Figure 2) as there are in the plot of revenue over time (Figure 1).

Transistor output has steadily expanded. Today we have reached over 10^{18} transistors a year. That is a hard number to contemplate. Patrick Gelsinger of Intel estimates that present transistor output equals the number of grains of rice produced globally each year. Over the years, I have used a variety of similar comparisons. At one stage, Edward O. Wilson, the well-known naturalist at Harvard, had estimated that there were perhaps 10^{16} to 10^{17} ants on earth. In the early 1990s, then, the semiconductor industry was producing a transistor for every ant. Now, the poor little ant has to carry a hundred of them around if he is going to get his share.

I have also estimated that the total number of printed characters produced globally every year—including all newspapers, magazines, photocopies, and computer printouts—is between 10^{17} and 10^{18}. Today, the semiconductor industry makes more transistors than the world's output of printed characters, and we sell them for less. This cost dimension is the key factor. To make this dimension clear, dividing annual revenue by transistor output provides a plot of the average price of a transistor (Figure 3).

Today, the cost of an average transistor has dropped to about a hundred nano-dollars. For transistors in dynamic random access memories (DRAMs), the cost is less. For transistors in microprocessors, the cost is a bit more. This cost reduction curve represents an amazing rate of change, and it is the basis for the large impact the semiconductor industry has had in making electronics so much more available.

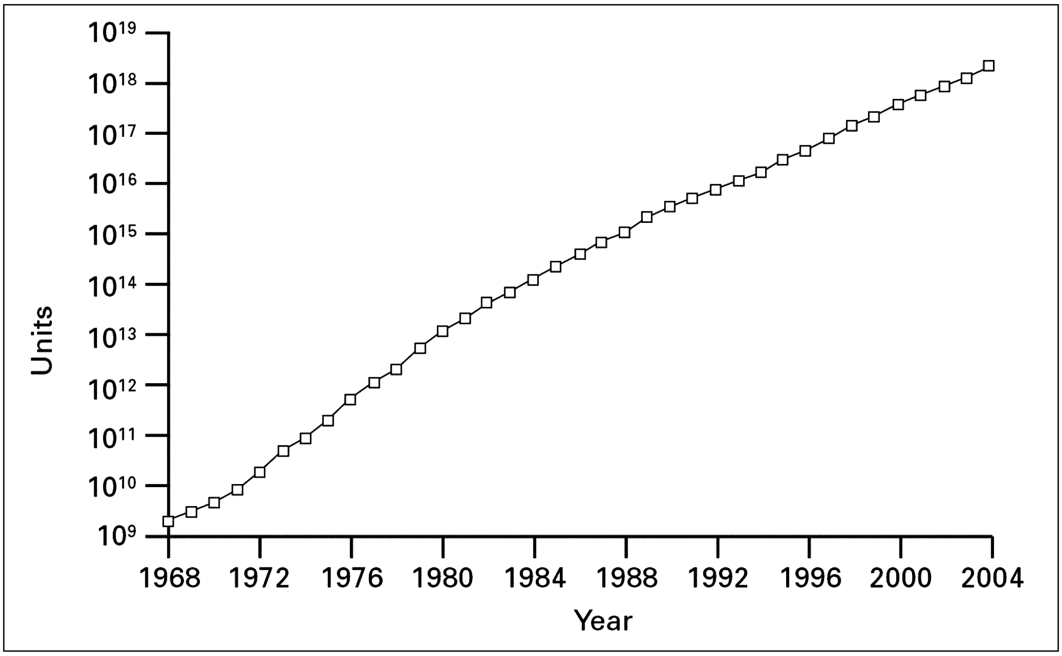


FIGURE 2. Total number of transistors shipped by the semiconductor industry (1968–2004). Source: Intel/WSTS, May 2005.

BACKGROUND

My interest in thinking about these kinds of plots dates back at least to 1964, when I was writing the paper that contains the first version of what became known as Moore's law. I was not alone in making projections. At a conference in New York City that same year, the IEEE convened a panel of executives from leading semiconductor companies: Texas Instruments, Motorola, Fairchild, General Electric, Zenith, and Westinghouse. Several of the panelists made predictions about the semiconductor industry. Patrick Haggerty of Texas Instruments, looking approximately ten years out, forecast that the industry would produce 750 million logic gates a year. I thought that was a huge number, and puzzled, "That is really perceptive. Could we actually get to something like that?" Harry Knowles from Westinghouse, who was considered the wild man of the group, said, "We're going to get 250,000 logic gates on a single wafer." At the time, my colleagues and I at Fairchild were struggling to produce just a handful. We thought Knowles's prediction was ridiculous. C. Lester Hogan of Motorola looked at expenses and said, "The cost of a fully processed wafer will be $10."

When you combine these predictions, they make a forecast for the entire semiconductor industry. If Haggerty were on target, the industry would produce 750 million logic gates a year. Using Knowles's "wild" figure of 250,000 logic gates per wafer meant that the industry would only use 3,000 wafers for this total output. If Hogan was correct, and the cost per processed wafer was $10, that would mean that the total manufacturing cost to produce the yearly output of the semiconductor industry would be $30,000! Somebody was wrong.

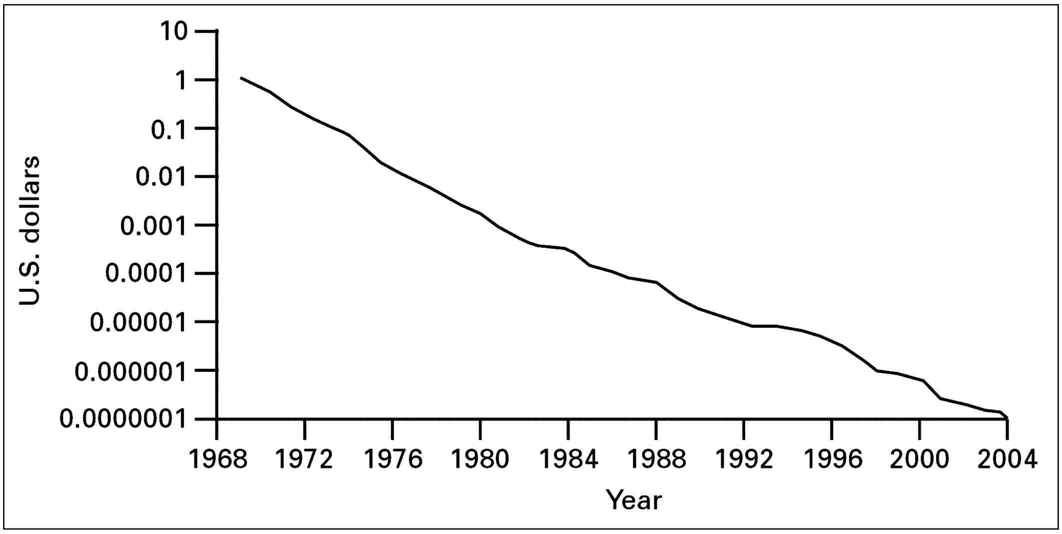


Figure 3. Average price of a transistor (1968–2004). Source: Intel/WSTS, May 2005.

As it turned out, the person who was the "most wrong" was Haggerty, the panelist I considered the most perceptive. His prediction of the number of logic gates that would be used turned out to be a ridiculously large underestimation. On the other hand, the industry actually achieved what Knowles foresaw, while I had labeled his suggestion as the ridiculous one. Even Hogan's forecast of $10 for a processed wafer was close to the mark, if you allow for inflation and make a cost-per-square-centimeter calculation. Today, the industry does not "do" $10 wafers, but we use wafers that are very much larger than the one-inch wafers that Hogan was talking about in 1964. Using a cost-per-area calculation, Hogan's prediction really was in the ballpark.

1965 PAPER

The suggestions of Haggerty, Knowles, and Hogan reflected the general views of the semiconductor industry around the time I was working on my 1965 projection. *Electronics* magazine had asked me to forecast what would happen in the next ten years to the semiconductor components industry. This was very early into the semiconductor integrated circuits era. The primary user of integrated circuits was the military. Integrated circuits were too expensive for use in commercial systems, costing significantly more than the equivalent circuit built out of individual components. Potential customers also had a variety of other objections. They were concerned with ensuring the reliability of integrated circuits when you could no longer measure the parameters of each element—the transistors, the resistors, and so on. With the integrated circuit, only the reliability of the whole device could be measured.

Critics also argued that, with integrated circuits, our yields would vanish. Yield is a critical concept in the semiconductor industry, meaning the percentage of acceptable devices actually produced on a wafer out of the total number of potential working devices. These critics knew that, at the time, we made transistors at yields in the

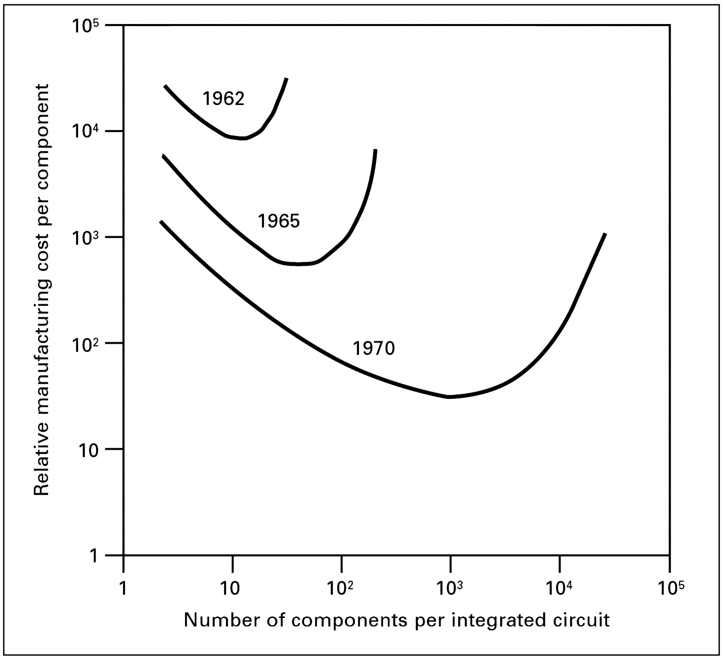


FIGURE 4. Manufacturing cost per component versus number of components per integrated circuit, from 1965 *Electronics* article.

10 to 20 percent range. They argued that for a circuit with eight transistors, taking 0.2 to the eighth power, you got an awfully small number for yield. Moreover, the integrated circuit's performance was below that obtained by using individual components, because of parasitics and other factors in the integrated circuits. The low yields argument reflected the fact that potential purchasers did not think that they would be able to get the actual supplies that they would need.

From my different perspective, as the director of the research laboratory at Fairchild Semiconductor, I could see some of the major developments that were coming. In my article in *Electronics*, I wanted to send the message that, looking forward, integrated circuits were going to be the route to significantly cheaper products. That was the principle message I was after.

To sharpen this economics message I analyzed the cost per component versus circuit complexity for integrated circuits. I plotted and projected this relationship in a series of curves (Figure 4), which suggested that, at a given time, there was a minimum manufacturing cost per component that was achieved by using a particular degree of complexity. At a lower complexity, one was not taking full advantage of the processing technology, and therefore costs increased. Beyond the optimal complexity point, the yields also dropped considerably, and hence costs increased. Importantly, I saw that the minimum cost per component point had been coming down quickly over several years, as the manufacturing technology improved. From this observation, I took my few data points and plotted a curve, extrapolating out for the ten years I had been asked to predict (Figure 5).

The last data point in this graph, the 1965 point, represents a device that we had at the time in the Fairchild laboratory with approximately sixty components, which

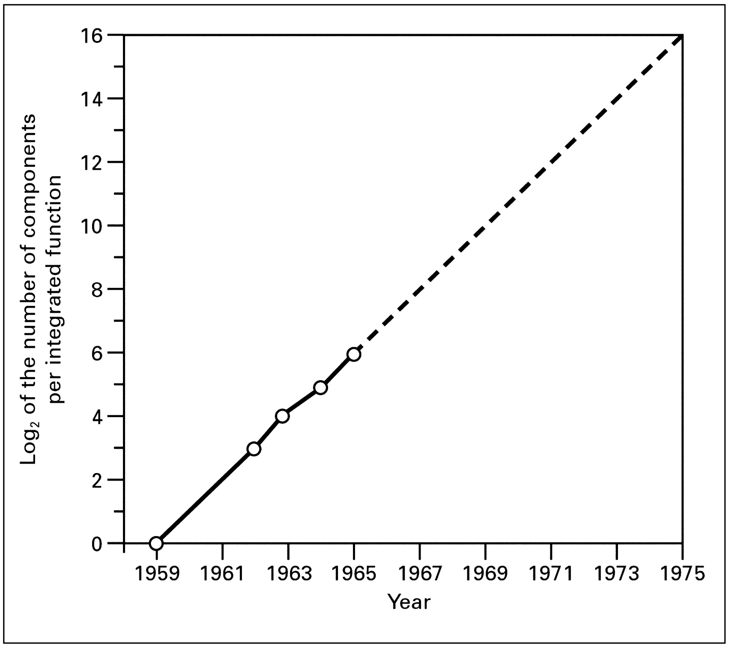


Figure 5. 1965 projection of number of components on an integrated circuit.

the company was going to introduce soon. The first data point on the graph represents the original planar transistor that we introduced in 1959. The planar transistor was the starting point for the integrated circuit's basic technology, so it deserved to be on this curve also.

Between the point for our 1959 planar transistor and our 1965 new device with sixty components were several points representing the Micrologic family of integrated circuits that Fairchild Semiconductor had introduced. Plotting these points using a log-base-two scale, I saw that the points fell closely along a line representing a doubling of complexity every year through 1965. To make my requested prediction, I simply extrapolated this same line for another decade, thereby predicting a thousandfold increase in complexity. The rather obscure log-base-two scale that I used on the vertical element of the graph made it a bit difficult to see that I was extrapolating from sixty to sixty thousand components. Nevertheless, the curve did seem to make sense with the existing data and some people who looked at this line and said, "That's a reasonable extrapolation."

1975 SPEECH

I never expected my extrapolation to be very precise. However, over the next ten years, as I plotted new data points, they actually scattered closely along my extrapolated curve (Figure 6). At the end of these ten years, I gave a talk at the IEEE International Electron Devices Meeting to show what had actually happened since my 1965 prediction, to analyze how the semiconductor industry had accomplished that degree of progress, and to make a prediction for upcoming years. To do this, I broke down the complexity curve into several contributing factors (Figure 7).

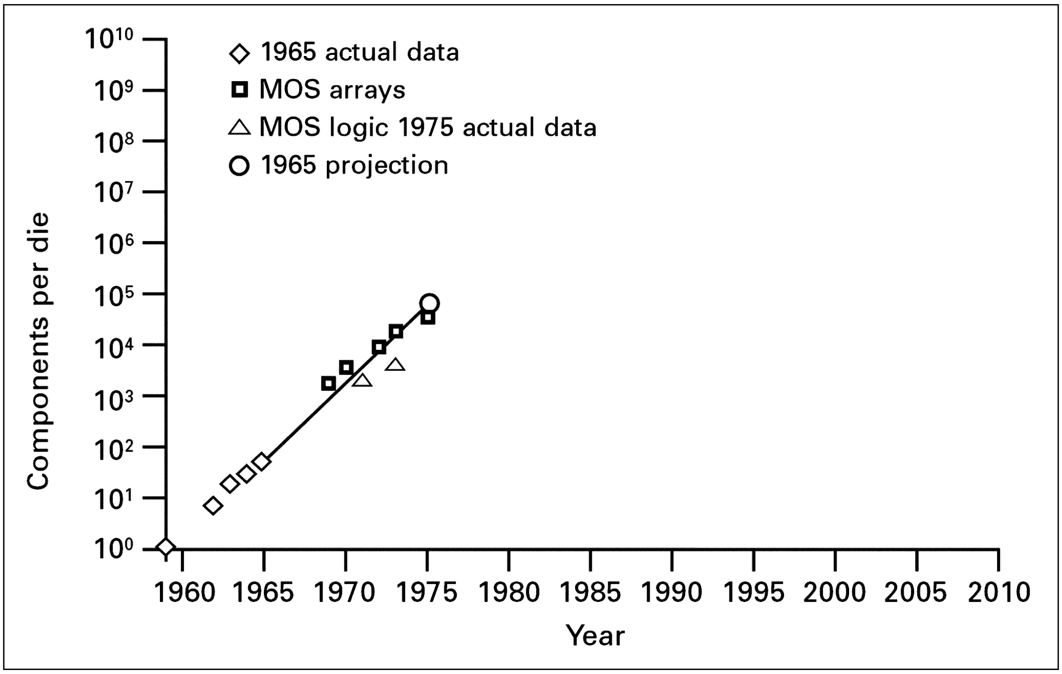


Figure 6. Integrated circuit complexity (1959–1975). Source: Intel.

One of the factors I named the "die size contribution." In the semiconductor industry, the term *die* is used for the area on a processed wafer that contains a single device. After a wafer is completely processed, the wafer is cut in to many "dice," each containing a single integrated circuit. The "die size contribution" factor in Figure 7 reflects how the semiconductor industry was making larger devices (with increased die sizes) and therefore had more area onto which to put components. A second, slightly larger contribution to the complexity increase was "dimension reduction." This was the shrinking of component dimensions, which led to an increase in the density. Multiplying these two contributions results in a curve that represents the combined effect on complexity growth of "die size and dimensions." This combined contribution was responsible for more than half of the progress that the industry had made on the complexity curve, but there remained a very considerable element that came from some other factor. On the graph, I labeled this factor the "contribution of device and circuit cleverness." This factor I identified with squeezing waste space out of the chip, getting rid of isolation structures and a variety of other things.

The last data point that I had for my 1975 talk was the component count for a charge-coupled device (CCD) memory that we were working on at Intel. With CCDs, the active areas are as close to one another as possible. There was no room left to squeeze. As a result, my argument was that, sometime soon after 1975, we were going to lose this "cleverness" factor, a factor that had contributed nearly half of the progress on the complexity curve. For simplicity's sake, I rounded this contribution to half of the total. With this loss, then, the complexity curve was going to change from doubling

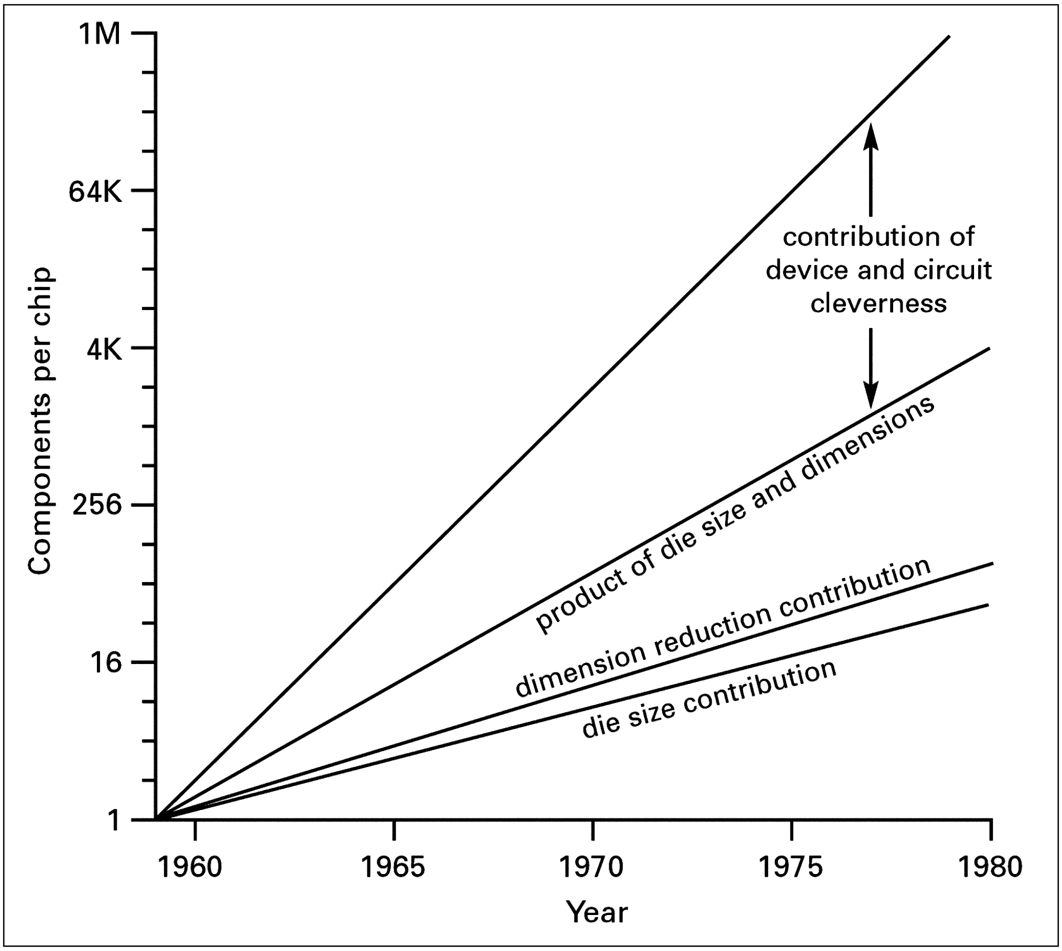


FIGURE 7. Resolution of complexity increase into contributing factors. Source: Intel.

every year to doubling every two years, and we would have to rely only on the two factors of increased die size and finer dimensions.

I knew too much. I was looking at our CCD memories, and the device we had nearly ready to go into production was 32 kilobits. We also had a 64 kilobit CCD memory coming along, and a 256 kilobit not too far behind the 64. I believed that those CCD memories were going to keep us doubling every year for another few years. I thought, "Well, I'm not going to change the slope right away. I'll give the rate a five-year rollover time" (Figure 8).

What I did not realize was that CCD memories were going to be a disaster. The same property that makes CCDs good imaging devices in such products as digital cameras makes them terrible memory devices: they are very sensitive to radiation. An alpha particle generated out of the packaging material for a CCD memory can completely wipe out several bits. This was a major problem. These were non-repeatable errors, with occasional random losses of bits of information, and we started to find

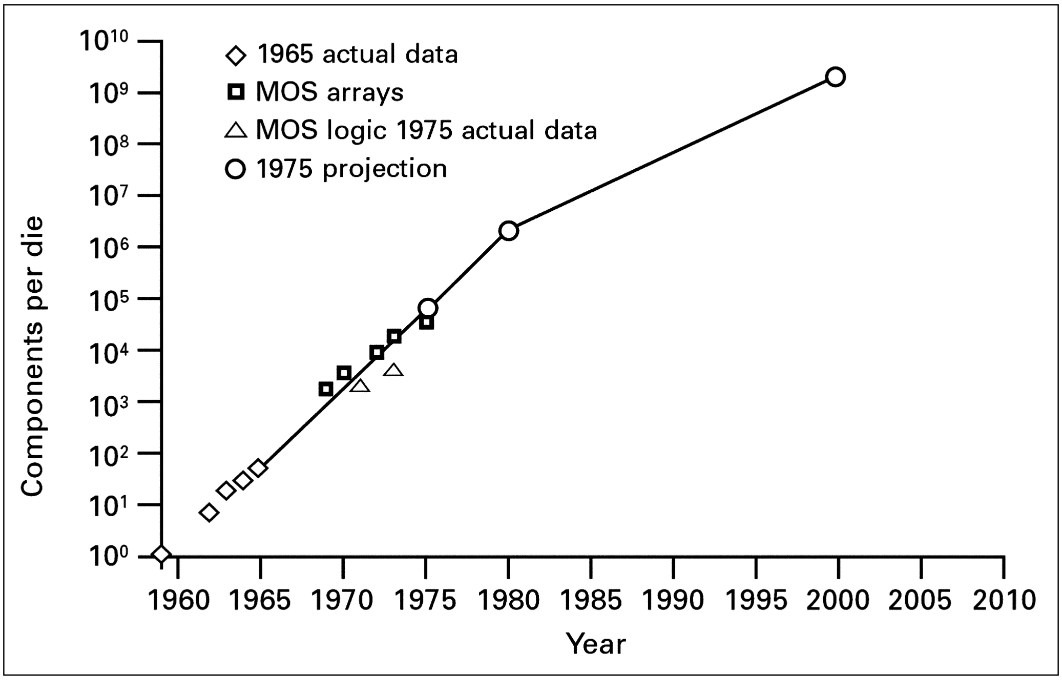


FIGURE 8. Integrated circuit complexity, 1975 projection. Source: Intel.

them in DRAMs as well. Our CCDs turned out to be very valuable for studying this alpha particle phenomenon, finding out what the problem was and getting to some solutions. However, we did not introduce any CCD memories after our first CCD memory product. The net result of the CCD experience was that, while I had predicted a five-year hiatus before the complexity slope would change, in fact the slope changed right away. Had I started the new slope, representing a doubling every two years, in 1975 instead of after the five-year rollover, my prediction would have been much more accurate. But I didn't (Figure 9).

OTHER "EXPONENTIALS": WAFER SIZE

I made a number of other extrapolations; some were just to demonstrate how ridiculous it is to extrapolate exponentials. In my 1975 talk, I described the contribution of die size increase to complexity growth and wrote: "In fact, the size of the wafers themselves have grown about as fast as has die size during the period under consideration and can be expected to continue to grow." One of my colleagues at Intel caught wind of that extrapolation and let me know that the 57-inch wafer predicted for the year 2000 did not quite come to pass.

Nonetheless, wafer size has grown dramatically, and I have to say that I am agreeably surprised by the size of the 300-mm wafers that the semiconductor industry uses today. To make the first planar transistor at Fairchild in 1959, we used three-quarter-inch wafers. In fact, one of my contributions to the semiconductor industry at that time was to show that if wafer size went above three-quarters of an

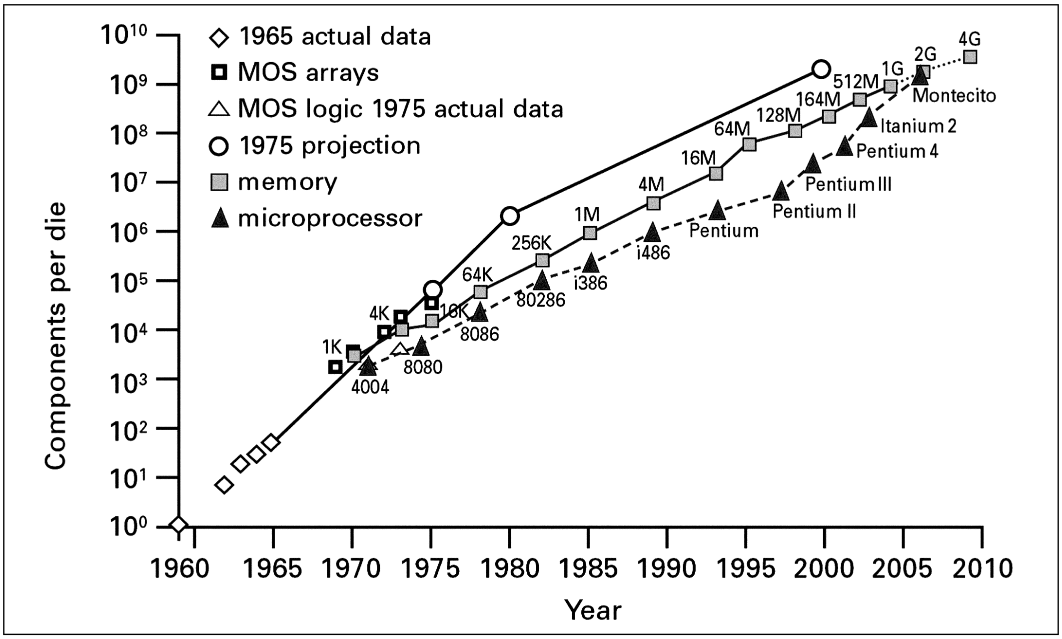
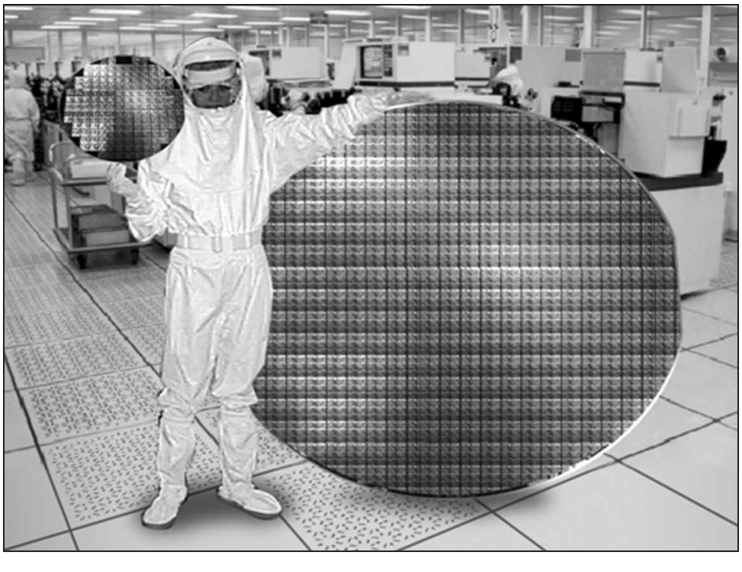


FIGURE 9. Integrated circuit complexity, actual data compared with 1975 projection. Source: Intel.

inch then yields would drop to zero because the quality of the material deteriorated so rapidly. The amount of technology that has gone into growing and slicing single crystals, with rapidly expanding diameters, is fantastic. Our next wafer size, 450 mm, will be the size of the kind of pizzas that can be bought at Price Club—about 18 inches. Those are monster pizzas.



A digitally manipulated photograph showing the ficticious 57-inch wafer. Courtesy of Intel.

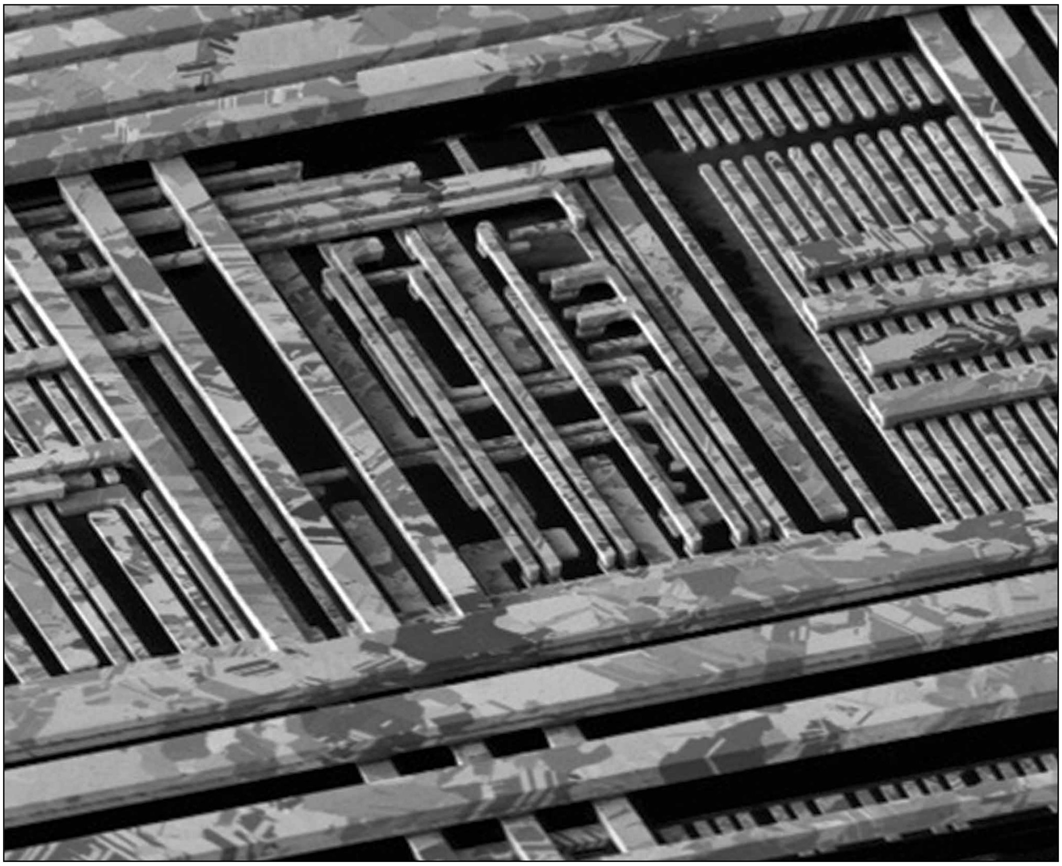
A 300mm wafer with U.S. nickel (approximate size of 1959 standard ¾-inch wafer) for scale. Courtesy of Intel.

OTHER "EXPONENTIALS": INTERCONNECTIONS

Just as wafer size has grown dramatically over the past forty years, so too has the "complexity" of interconnection technology, the system of metal pathways that connect the many components of an integrated circuit. As with wafer development, this growth in interconnection technology has required an impressive amount of materials innovation. The intricacy of contemporary interconnects can be visualized by examining an electron micrograph of the copper interconnections for a device where all the insulating regions have been dissolved away in order to highlight the complexity of the interconnection system. The crystal grains of the copper in the top level interconnects are visible. Moving down the levels, the interconnects become smaller still.

A more modern process technology, the 90 nanometer generation, is now being introduced into production. It has seven layers of metal interconnections, separated by low dielectric-constant insulators, with a very thin layer of active silicon buried at the very bottom level (Figure 10). This is an amazingly complex structure that we have evolved.

There are many materials involved in a contemporary transistor (Figure 11, left): nickel silicide in some areas, silicon nitride in others. Moreover, we use strained silicon in these devices, producing the straining in one direction by adding germanium to the silicon, using a silicon carbon-nitride mixture for straining in the other direction. In some devices, the silicon is compressed, in others it is expanded, depending



A region of copper interconnects for an Intel logic device from 2001. Courtesy of Intel.

on whether it is the mobility of holes or electrons that one is trying to increase. Exotic compounds like tantalum nitride are used as barriers to stabilize the performance of the copper interconnections (Figure 11, right). The simple, old, silicon-oxide-aluminum system for semiconductor devices has been replaced by a much more complex system of materials.

DECREASING DIMENSIONS

These complex material systems have become necessary for maintaining one of the principal factors that produces the complexity curve: the continual decrease in the dimensions of components.

The top curve in Figure 12 represents what Intel has actually achieved in reducing feature size. This progress has been along a fairly constant slope, with a new generation of technology introduced about every three years, and each generation doubling the component density. This is the general developmental algorithm the industry has followed. In the beginning the industry did not analyze the pace explicitly. Increasingly we recognized that there was a definite pattern in what was happening, and we deliberately tried to continue it. With the advent of the International Technology Roadmap

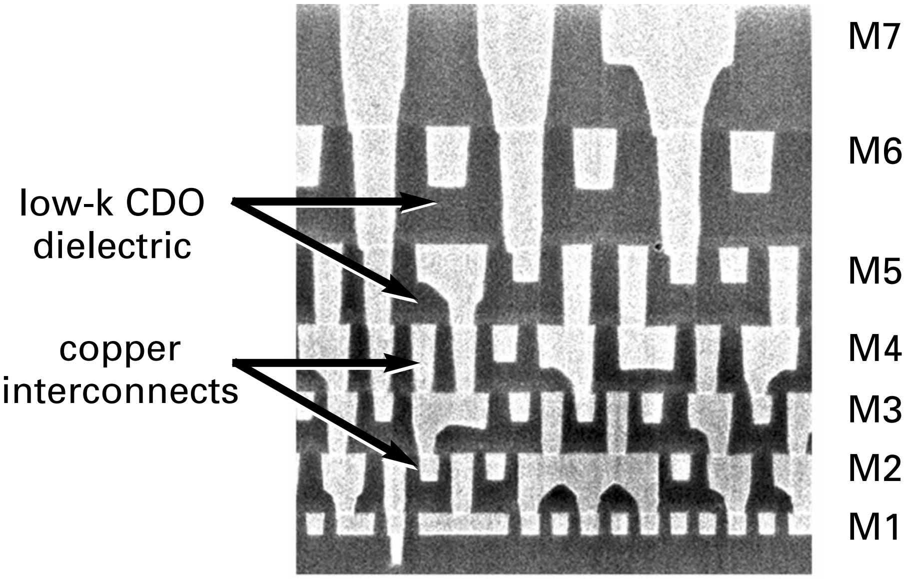


FIGURE 10. Side view of seven layers of metal interconnects in the 90-nm process technology. Source: Intel.

for Semiconductors produced by the Semiconductor Industry Association, the goal of continuing this slope has been formalized, with a new generation of process technology coming on line every three years. That was a reasonable goal to set.

The nature of the semiconductor business is such that companies have to be at the leading edge of the technology to be competitive. The reason is that the semiconductor industry is really selling real estate. The price of that real estate has been nearly constant for as long as I have been in the business: on the order of a billion dollars an acre. It used to be a few billion dollars an acre, and microprocessors now are about

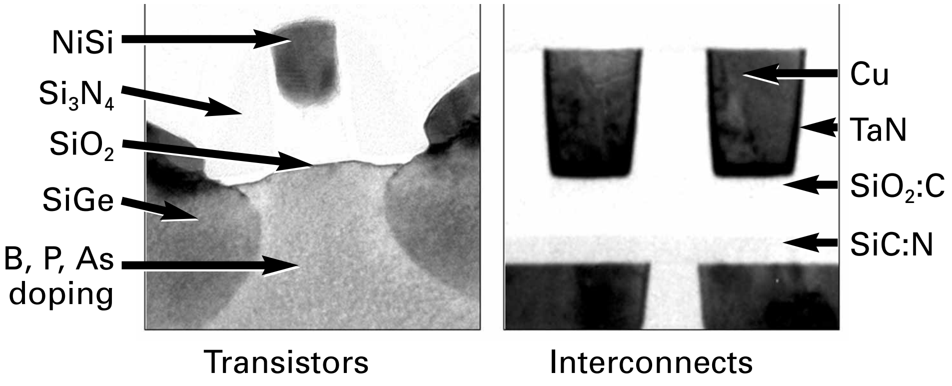


FIGURE 11. Micrographs of a transistor and interconnects created using the 90-nm process. Source: Intel.

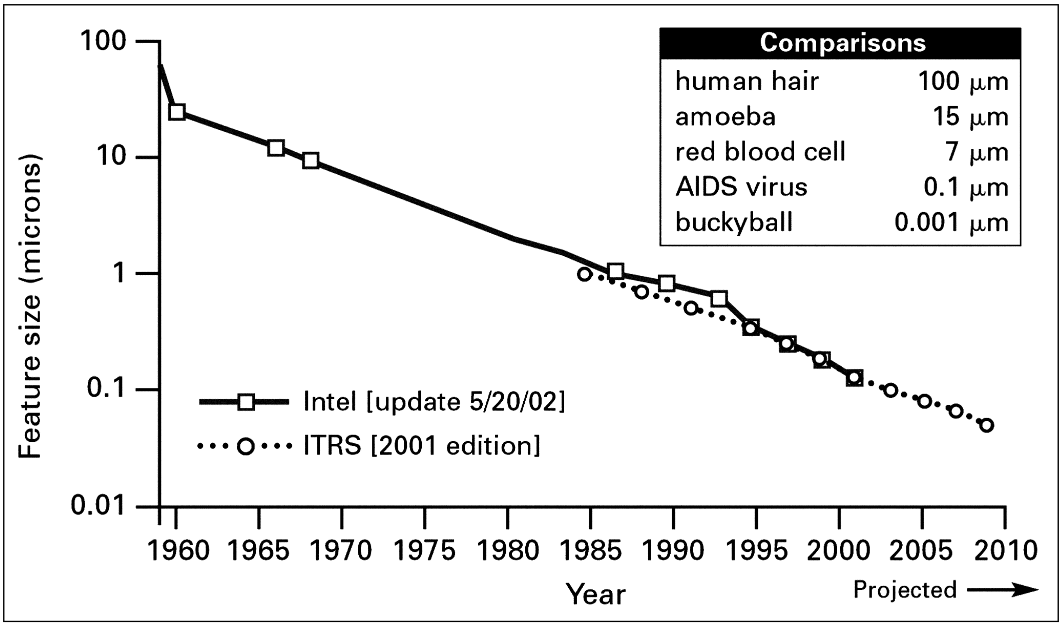


FIGURE 12. Decreasing dimensions: minimum feature size of integrated circuits (1963–2010). Source: Intel, post 1996 trend data provided by *SIA International Technology Roadmap for Semiconductors* (ITRS). (ITRS DRAM Half-Pitch vs. Intel "Lithography").

$2 billion an acre. Memory today is about $0.8 billion. On balance, silicon real estate has been steady on the order of a billion dollars an acre. I used to joke that this was why Japanese firms were such formidable competitors: silicon real estate was about the price of land in Tokyo in the 1980s.

As the real estate perspective shows, companies that do not stay near the leading edge of process technology suffer from a cost disadvantage. They are not exploiting the available enhanced densities, thereby are not making the most out of some very expensive real estate. In addition, in the semiconductor industry, the most profitable products have been leading edge devices. If companies do not keep to the leading edge, their products suffer a performance disadvantage. Straying from the most advanced technology, the combination of cost and performance disadvantages is competitively catastrophic.

What happens with this push to the leading edge? What happened, of course, is that we changed the slope (Figure 13). When the industry fully recognized that we were truly on a pace of a new process technology generation every three years, we started to shift to a new generation every two years to get a bit ahead of the competition. As a result, instead of slowing, this trend to smaller and smaller dimensions has actually accelerated as a result of people recognizing the slope. I think that this is a strong example of how awareness of Moore's law-type trends has driven the industry. Everybody recognizes that they have to keep up with this curve, or they will fall behind.

While the complexity curve can be understood intellectually, it is interesting to approach it from a more tangible point of view in order to get a feel for what this

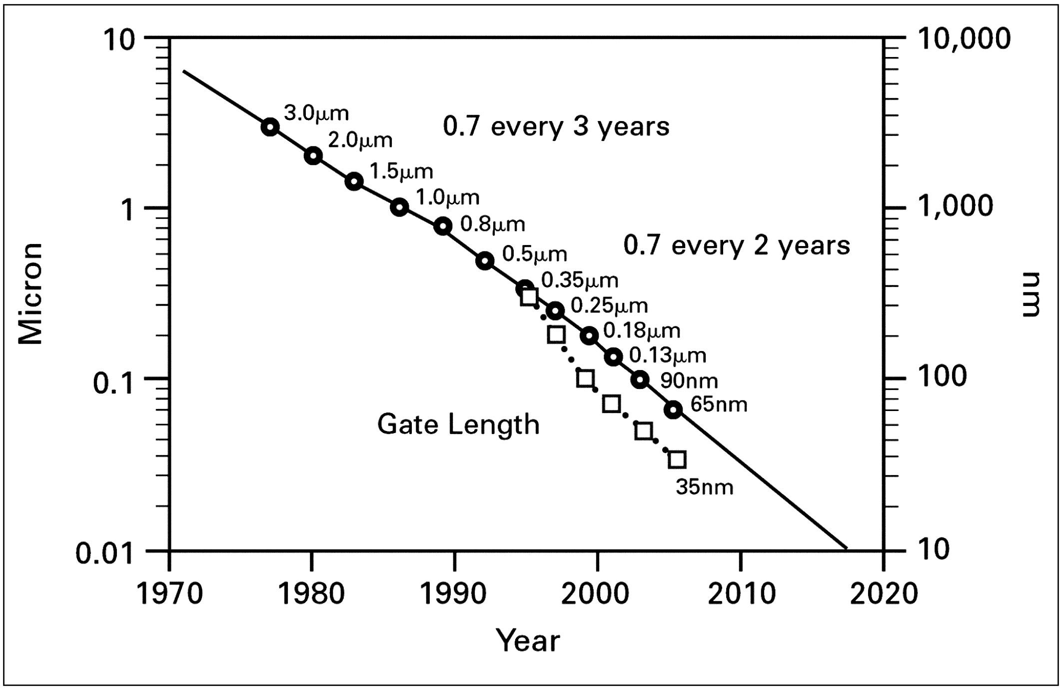


FIGURE 13. Plot of new technology generation introductions (1975–2005). Source: Intel.

pace of change has produced. Figure 14 shows one contact produced on a device using the generation of process technology in 1978. Twenty-four years later, an entire six-transistor memory cell occupies just a fraction of the area of the 1978 vintage single contact. A series of incremental changes, over a sufficient period, results in dramatically different products.

EQUIPMENT COSTS

Keeping to the complexity curve for semiconductor devices has entailed a corresponding increase in the complexity of semiconductor manufacturing equipment. Modern 193 nanometer exposure systems use argon fluoride excimer lasers, among other things; these are really very sophisticated and complicated pieces of equipment. Nevertheless, to keep on the complexity curve, we are going to have to make a step beyond this equipment before too long. The industry is working on a 13 nanometer, extreme ultraviolet exposure system: essentially more than an order of magnitude decrease in the wavelength. These 13 nanometer machines require completely reflective optics. No materials are fully transparent in this wavelength range, and mirrors are not very good reflectors of these wavelengths either. One of these 13 nanometer systems uses thirty-plus reflections, each with only something like 0.6 or 0.7 reflectivity. This presents a definite challenge. The optical surfaces have to be better than those of the Hubble Space Telescope, in order for us to get the kind of performance that we want.

These equipment challenges have kept the semiconductor industry on another exponential, in the cost of lithography equipment (Figure 15). In fact, you can plot a

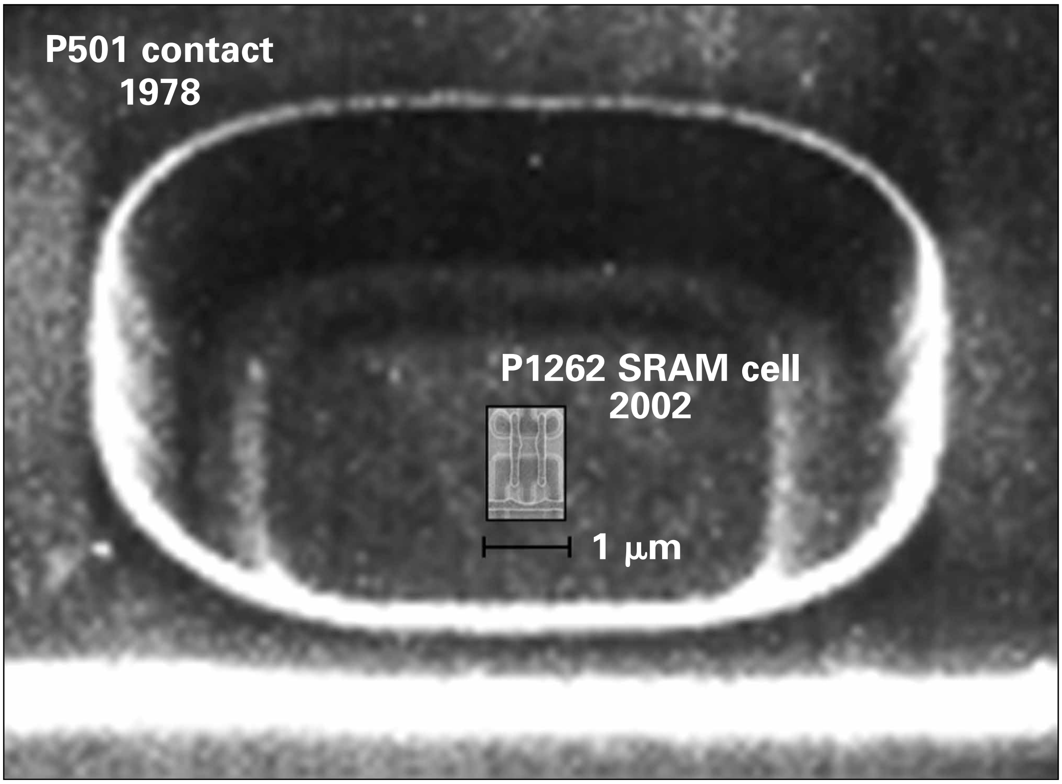


FIGURE 14. Size comparison of a single contact from 1978 with a full SCRAM cell from 2002. Source: Intel.

price exponential for most types of semiconductor manufacturing equipment. This presents an interesting economic challenge. The equipment keeps going up in cost exponentially, but the semiconductor industry is not growing as rapidly anymore. Capital costs are rising faster than revenue. Nevertheless semiconductor companies have to stay on the leading edge of process technology or they suffer cost and performance disadvantages.

MATERIALS CHALLENGES

In addition to the equipment challenges for producing smaller and smaller features, we also encounter materials challenges. As component size decreases, we use thinner and thinner layers of insulators. With this thinness, electrical leakage and other factors are of greater concern. To see how dramatic this issue is, consider a transmission electron micrograph of a gate area on a component produced by the 90 nanometer production process (Figure 16, left).

At the bottom of the pictured area, the individual atoms in the silicon substrate are visible. The middle section, the insulating silicon dioxide layer, is no thicker than a couple of molecular layers. At the top, the gate is again formed by silicon. This leading edge technology has a problem: leakage current because of quantum mechanical

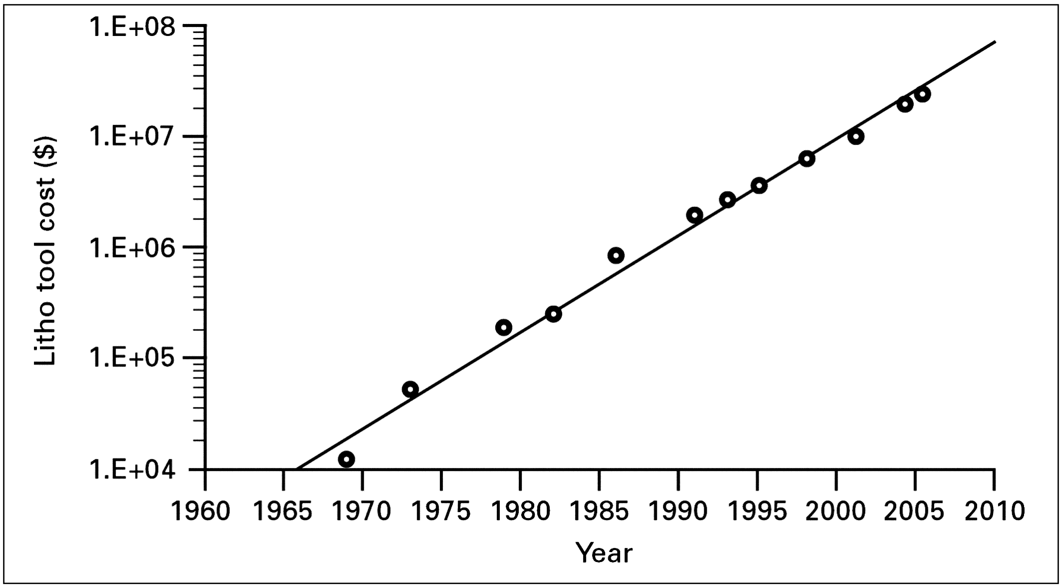
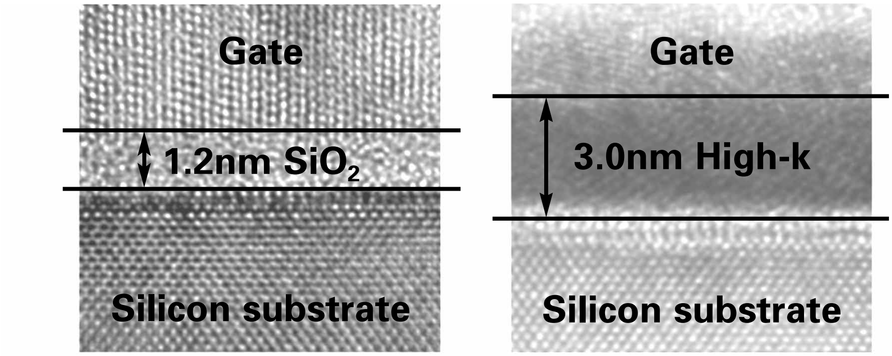


FIGURE 15. Cost of process equipment for photo lithography (1969–2005). Source: Intel.

tunneling through the thin layer. This problem can be minimized if we change to a new insulating material with a high dielectric constant. We have a material that we are working on now that allows us to make this kind of dramatic change (Figure 16, right). With this new insulating material, the capacitance is preserved. In fact, it increases, which means a higher electrical field is transferred to the silicon substrate, resulting in better performance. More remarkably, the leakage current goes down a



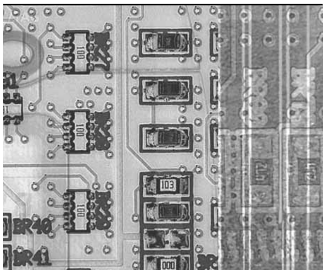
	90nm process	Experimental high-k
Capacitance	1X	1.6X
Leakage	1X	< 0.01X

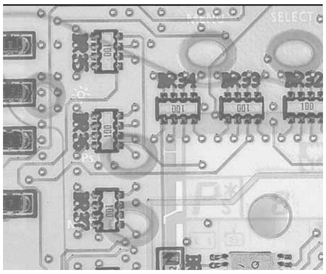
FIGURE 16. Materials challenges: leakage and dielectrics. Source: Intel.

hundredfold. Those are the kinds of changes that new materials allow us to make. They are not easy. A tremendous amount of work went into finding a material with the correct dielectric capabilities that was also stable enough to withstand processing and could tolerate these high electric fields.

LOOKING FORWARD

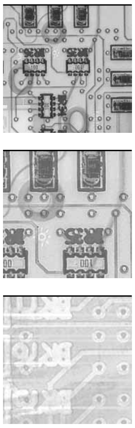
Having outlined my general approach to understanding the semiconductor industry and having identified some key factors for keeping on the complexity curve, one might ask, "When is it all going to end?" I have been asked that question at least a hundred times this year. The answer is: "Not very soon." I can see the complexity curve lasting for at least as long now as I ever could in the past. I always could see what we were going to do to make the next two or three technology generations happen on the curve. Today, as I speak with the Intel research and development staff members, they are looking out even further. Now I can see what we are going to do for the next four generations, which is further than we have ever been able to look out before. Many advances have to happen to make those future generations occur, but we are confident the problems are going to be solved in time to make it all happen. It is amazing what a group of dedicated scientists and engineers can do, as the past forty years have shown. I do not see an end in sight, with the caveat that I can only see a decade or so ahead.





PART THREE

REFLECTIONS



CHAPTER 8

REFLECTIONS ON MOORE'S LAW

David C. Brock

This final chapter offers reflections on and observations about Moore's law and its history as well as predictions for the future. These insights are gleaned from the speakers that the Chemical Heritage Foundation gathered for its 2005 symposium, Moore's Law at Forty,[1] all of whom have been deeply engaged, in different ways, with the extraordinary development of microelectronics and its consequences. The reflections and observations fall into two groups. The first deals with the material realities of Moore's law, the story of chemistry and materials in the semiconductor technology that Moore's law describes. The second addresses the efforts required to create exponential technological change and the consequences of this change.

THE MATERIAL REALITIES OF MOORE'S LAW

The combined perspectives of three individuals—Harry Sello, Elsa Reichmanis, and Raj Gupta—represent a survey of the material reality of Moore's law as based in technologies for creating electronics through the transformation of materials by chemical, physical, and mechanical means. Sello's contribution outlined the diversity of issues that chemists addressed in the early years of the semiconductor industry to establish its basic manufacturing capability. Reichmanis's perspective opened up one facet of Sello's survey of chemical challenges, detailing the story of photoresist chemists' experience of keeping apace with and empowering Moore's law. Finally, Gupta reviewed the general, transformative impact of Moore's law on the industrial sector that has provided the raw materials for the silicon revolution: the chemical industry.

Laying the Foundations: Making Silicon Work

In the mid-1950s Harry Sello was a physical chemist working in a hotbed of organic chemistry research. In this period he took a telephone call during which he was quizzed about semiconductors. Sello had made a name for himself as a chemist during his tenure at the Shell Development Laboratory in Emeryville, California—one of the West Coast's premier industrial research centers. The individual who placed the call to Sello was none other than William Shockley. At the time, Shockley was seeking to gird his new organization—the Shockley Semiconductor Laboratory—with experts in physical and organic chemistry. Sello, who was familiar with Shockley's role in launching the then-new transistor age, needed little convincing to sign on. At Shockley Semiconductor, and then later at Fairchild Semiconductor, Sello worked at the forefront of the manufacturing process development that gave rise to the spread of silicon transistors and integrated circuits. He stood at a primary intersection of the domains of chemistry and the new electronics. Reflecting on the forty-year history of Moore's law, Sello highlighted the chemical issues that set the direction for the semiconductor industry, the path of Moore's law. Sello's highlights reveal not only the early contributions of chemistry to the establishment of the dynamic of Moore's law but also the diversity of roles that a chemist could play in the expansion of the semiconductor industry itself.

At Shockley Semiconductor, Sello worked on chemical issues that spanned the entire manufacturing process. He designed and built a crucial piece of equipment for an early stage of the process—a diffusion furnace. Such a furnace, used to carefully diffuse dopants into silicon wafers to form the crucial junctions at the heart of transistors, was no simple order. The furnace had to produce very high temperatures, and these temperatures needed to remain constant both in time and in space throughout the furnace's interior. Why would the creation of such a furnace fall to a chemist like Sello? As a chemist adept at using heat and furnaces to promote chemical reactions, Sello was a clear choice for the project.

At the other end of the semiconductor manufacturing process line from the diffusion furnaces, Sello confronted another issue, one that was just as suitable for a chemist to tackle. In the batch production of many transistors on a single silicon wafer, the last step before testing and assembling the transistors was their physical separation from the wafer. At Shockley Semiconductor, and later at other firms, process engineers selected acid etching for this separation step. In early examples of this approach, a production worker would add, by hand, a touch of melted black wax to cover each transistor on a wafer. When cooled, the cap of wax protected the transistors from a fast acid etching step that removed the wafer from the transistors. William Shockley found the procedure too crude. At Shockley's prompting, Sello examined a cornucopia of waxes to see if any might be good masks for this etching step as well as being amenable to deposition on the wafers by an evaporation procedure. Shockley and Sello thought, if they could batch produce transistors, they could batch deposit dots of wax.

Sello also worked to introduce the discipline of a more traditional chemical manufacturing operation into the then rather freewheeling use of materials rampant in semiconductor processing. One of Sello's watchwords in this push was "safety," and with it he and several of his colleagues sought to bring the nascent silicon semiconductor industry in line with more established chemical operations in terms of the handling and disposal of powerful reagents. Another of Sello's generalized chemical concerns was the procurement of these very same reagents and other materials. He fought an uphill battle to acquire materials for the laboratory with the required levels of chemical purity. Because transistor manufacturing centered on unprecedented control over the introduction of particular impurities into silicon, the laboratory needed materials that exceeded the purity available in off-the shelf "chemically pure" reagents. Obtaining these ultra-pure materials from suppliers in the relatively small quantities required—bottles rather than tank cars—represented a true challenge.

While many of these challenges awaited Sello when he moved to the newly established Fairchild Semiconductor in the late 1950s, new chemical problems greeted him as well. In particular, Sello joined Fairchild's effort to get its new kind of transistor—the planar transistor—into production. History would later reveal the importance of this effort, for the first planar transistor marked the start of the path of technology development described by Moore's law. The planar transistor, like the first readily manufacturable integrated circuits that would soon follow it, relied on the formation and the use of layers of silicon dioxide on the silicon wafers in the fabrication process. Sello described the importance of this oxide when reflecting on four decades of Moore's law: "The success of the integrated circuit industry is due to that wonderful material that grows naturally on silicon."[2]

One of the key uses of oxide layers in the production of planar transistors and integrated circuits was as a diffusion mask. That is, the oxide layer was physically patterned, leaving some areas of the silicon wafer coated by oxide, and some areas uncovered. The covered areas were closed off from impurity diffusion steps, while the uncovered areas were open to them. In this way, devices were formed. To pattern the oxide layer, Fairchild Semiconductor relied on the technology of photolithography—a technology that has remained at the very core of semiconductor development for the ensuing four decades of Moore's law.

In the lithographic approach, a layer of photoresist—a light-sensitive polymer—was coated on the oxide. The desired pattern was projected onto the photoresist, with the light-exposed regions of the photoresist changing their chemical structure in response. The changed and unchanged regions of the photoresist possessed a difference in how readily they were removed from the oxide by a chemical wash. The photoresist that remained controlled an acid-etching step for the oxide, resulting in the removal of some areas of the oxide but not others. The result was the desired patterning of the oxide for the diffusion operation.

It was clear to the scientists, engineers, and technicians of Fairchild Semiconductor that the behavior of the photoresist was critical to the feasibility of the entire lithographic scheme. Sello's photoresist challenge at Fairchild was a problem of "lifting," a tendency for the photoresist to have adherence problems near the edges of features, allowing etchants and other materials to creep underneath the photoresist and attack the device. This was a classical challenge of chemistry and of materials: how could Sello reformulate the resists to improve their adhesion while retaining other desired properties? While he and his colleagues made several advances, adhesion remains an issue with photoresists to the present day.

While problem solving on the manufacturing line required the intervention of chemists like Sello, their process expertise was also required for device design at a fundamental level. Indeed, across the entire history of both the semiconductor industry and Moore's law, there has been a close coupling of device design with manufacturing process. That is, the material realities of an actual, economically advantageous manufacturing process imposed particular "design rules" that device engineers and physicists used to devise new semiconductor products.

For example, a particular manufacturing process will allow a specific range of electrical isolation characteristics. The resulting design rules take this range into account, in the form of spacing limits for various features of a device. In this way, the realities of the fabrication process were embodied in the design of new devices before they ever reached the manufacturing line. Sello himself worked on just such a translation of material reality into design rules in the early years of integrated circuit technology. He identified one cause for the failure of some early integrated circuits: the migration of aluminum material in the metal web of interconnections that lay atop an integrated circuit, electrically connecting its constituent components. In brief, with particular thicknesses and widths of aluminum lines carrying particular amounts of electricity, the aluminum of the lines would migrate, causing gaps in the web of interconnections and a failure of the device. To prevent such occurrences, different thicknesses, widths, and spacings of the aluminum interconnections were required. These requirements were translated into new design rules, so that subsequent devices avoided the migration phenomenon. This feedback of the material realities of the production process into the design of new devices was a sustaining dynamic for the ongoing realization of Moore's law.

Across his decades-long career at Fairchild, Sello spearheaded other efforts in which chemists played an important role in making silicon work to realize Moore's law. Teams of chemists worked to invent new manufacturing processes for new generations of semiconductor devices. For example, a team in the research and development laboratory of Fairchild—consisting of Edward Snow, a physicist; Bruce Deal, a chemist; and Andrew Grove, a chemical engineer—determined that contamination by sodium and other alkali metals was particularly destructive for a promising new form of transistor, the MOS transistor (so named by acronym for the layers of material employed in its formation: metal-oxide-semiconductor). In response to this finding, Sello and a team of process chemists, engineers, and technicians developed a new manufacturing process—the "Planar 2" process—for MOS devices that minimized alkali contamination.

In addition, at the instruction of Gordon Moore, Sello developed a team of chemists and others to provide "sustaining engineering" to existing production lines and processes. When a particular line experienced problems, Sello sent a team of Ph.D.-level researchers to the factory floor to run the line, identify the derangement and resolve it. Closely observing existing processes and developing new ones, chemists like Sello constantly and continually helped to produce the means for the semiconductor industry to realize Moore's law.

While Sello's reflections zeroed in on the central role of the chemist within semiconductor manufacturing process development, he pointed as well to other areas in which chemists made significant contributions. They were key to developing new forms of packaging for silicon chips, which increasingly became the largest factor in the overall cost of a finished semiconductor device. They were also key to technology transfer: getting a process to work in a new geographical and institutional location. These transfers were important within a single firm, for example, when opening a new fabrication facility and between firms in partnerships, acquisitions, or the direct purchase of process technology. In all these areas, looking from the past to the future of Moore's law, Sello predicted that the opportunities for chemists to make important contributions are as great today as they were in the past. Great materials challenges await chemists who will continue to make silicon work, to follow Moore's law in the years ahead, and to exploit new materials—such as carbon nanotubes and organic semiconductors—to extend the possibilities of electronics.

Chemical Imperatives: Keeping to the Curve

Elsa Reichmanis has devoted her entire professional career to accommodating a constant chemical imperative in the ongoing realization of Moore's law: the design and creation of photoresist materials. Photoresists, in Reichmanis's view, have been essential to the realization of Moore's law. Echoing the basic message of Moore's law, Reichmanis maintained that cost has been the primary driver in the semiconductor industry's move from the early era of multi-inch scale transistors to the present nanometer scale devices. An exponential reduction in cost and rise in complexity has been achieved based on a number of factors—most prominently, reduction of feature size, improvement of yields, and increase of wafer size. To realize the first two factors—smaller feature size and improved yields—the burden has consistently fallen on lithography, the primary technology for patterning integrated circuits. Because of their place at the center of lithographic technology, photoresists—and the chemists who design and produce them—have played an essential role.

Photoresists are, as Reichmanis informally termed them, "the gloop laid down on silicon wafers" in order to form patterns. To understand why photoresists are key to fabricating ever-smaller patterns on integrated circuits, a review of the basics of lithographic technology is useful. To start, a silicon wafer is coated with a photoresist—a photoactive polymer-based material. Light is projected through a patterned mask onto the photoresist. In response to this exposure, areas of the photoresist change their chemical properties. After a developing process, the pattern has been transferred to the photoresist. Subsequent etching processes then transfer the photoresist pattern to the underlying substrate. After the pattern has been transferred to the substrate, the remaining photoresist is stripped off, and an additional layer of material is coated onto the substrate. To appropriately pattern these additional layers, the entire lithography sequence involving the photoresist is repeated. In short, integrated circuits are built up from multiple, patterned layers of material. The creation of each and every patterned layer involves the use of photoresist in a lithographic process.

As the semiconductor industry has continually pushed lithography technology in order to create smaller features and achieve improved yields, it has thereby created an ongoing chemical imperative for the innovation of new photoresists. In the development of lithography technology, a principal metric of advance has been the employment of ever shorter wavelengths of light in the process. Shorter wavelengths, paired with new photoresists capable of interacting with them, have allowed smaller features to be created. For the past three decades, lithographic processing has been carried out by using advanced, automated, and expensive manufacturing equipment known in the silicon community as process "tools." During this time the development of lithography technology has necessitated the close collaboration and coordination of a variety of technologists. This has very much been the case in the development of photoresists.

Reichmanis noted that, while chemists like her have no doubt played a large role in the development of photoresists, they have had to calibrate their efforts with those of semiconductor manufacturing process engineers, device designers, and tool designers. As recounted by Reichmanis, the photoresist designer faced, and still faces, a long list of desired properties to be held by the new material. Sensitivity is required, since photoresists must be highly responsive to light to achieve an economical through-put rate for the overall lithographic process. High contrast, or resolution, is needed, for the material must exhibit ultrafine response to the wavelength of light employed to create the smallest possible features, and thus, low-cost devices. High line width control is desired, whereby the photoresist can accept the pattern projected onto it with great fidelity, neither broadening nor narrowing the intended features. The photoresist must produce a tolerable defect density, meaning that the overall performance of the photoresist must contribute to an economically viable overall yield for the semiconductor manufacturing process. Good etching resistance is required, meaning that the developed photoresist is able to properly survive its exposure to powerful etching mixtures in the lithography process through which patterns are transferred to the underlying substrate. Lastly the new photoresist needs good adhesion, meaning that the photoresist will uniformly and consistently stick to the surface of the semiconductor substrate until the stage in the process when the developed resist is removed or stripped from the substrate.

The photoresist designer must also aim to secure for his or her new material a set of properties commonly sought for chemical products in general. Among these general desiderata is consistency, that is, that within a given sample the material is uniform. Sufficient shelf life is another; meaning that the material retains its desired properties and functionality for an adequate period. Another crucial attribute is a sufficiently low cost, for the photoresist itself must be an economically viable consumable for it to meet the cost requirements of its semiconductor industry users.

It is one thing for photoresist designers to ascertain a specific set of desired properties for a new material. It is quite another matter to realize these aims and successfully introduce a new photoresist into a new generation of lithographic technology. As Reichmanis recalled, the photoresist community learned an important lesson during the 1980s about the imperatives and vicissitudes of developing a successful new generation of photoresists that would keep apace with Moore's law. In the late 1970s members of the silicon community discerned that the developmental trend of Moore's law would, in roughly a decade, require a new generation of lithography technology. This new lithography technology, they reasoned, would need to move from the use of near and mid-range ultraviolet radiation for patterning integrated circuits to the employment of "deep-UV" radiation. Deep-UV lithography would use shorter wavelength light (254 nm) in order to produce the smaller, lower-cost devices and the increased complexity of integrated circuits that Moore's law predicted. However, as photoresist chemists looked at deep-UV lithography, they concluded that the then-traditional photoresists simply would not work: they would not have the correct absorbance response to the new wavelengths of light. This called for a major step forward in materials design.

In the early 1980s photoresist chemists achieved what Reichmanis termed a "revolutionary change" in the chemistry of photoresists. This advance was the development of the chemical amplification technique, wherein great sensitivity was achieved for the new class of deep-UV photoresists. In the chemical amplification method, a catalytic compound in the photoresist is activated by exposure to radiation in the lithographic process. This activated catalyst, in turn, prompts a cascade of chemical transformations in the photoresist, leading to the desired performance.

While the chemical amplification innovation was an important step forward for the photoresist community, a variety of problems remained with the new material. Adequate etch resistance had yet to be achieved. Indeed, chemical amplification introduced new problems. Chemical amplification required the wafer to be baked at an elevated temperature after exposure to the deep-UV radiation for the photoresist to develop properly. This baking procedure, however, initially caused intolerable changes in the dimensions of the pattern transferred to the photoresist—it had poor line-width control. It would take the better part of the 1980s for the photoresist community to tackle these additional challenges. The new deep-UV photoresists were widely adopted by the semiconductor industry in the late 1980s as part of its embrace of the new lithography technology generation. The photoresist community noted that it had taken nearly twelve years for the new material to move from design to invention to introduction. The community had learned that for it to play its required role in empowering the semiconductor industry to keep up with the developmental curve of Moore's law, they would have to look a decade ahead.

It was with just such a forward-looking orientation that photoresist chemists like Reichmanis greeted the new decade of the 1990s. As had been the case in the late 1970s, photoresist chemists again saw that a new generation of lithography technology was on the horizon. The semiconductor industry showed no sign of deviating from Moore's law, and the new generation of technology, employing still deeper UV radiation (193 nm), would be required to continue the industry's unending "drive to even still smaller features," as Reichmanis put it. However, there was an important difference between the photoresist community's situation in the early 1990s as compared with the late 1970s. In the early 1990s the Semiconductor Industry Association (SIA) had formalized, in great detail, the technological developments that it required for the continued fulfillment of Moore's law. The "technology roadmap" created by the SIA not only explicitly transformed Moore's law from a prediction to a self-fulfilling prophecy, it spelled out what needed to be accomplished, and when. As Reichmanis ascertained, "Advances in the [process] technology today are largely driven by the Semiconductor Industry Association."

In the early 1990s the chemical imperative faced by the photoresist community was to design a new material that was structurally different from earlier photoresists and was functionally superior. Reichmanis played a central role in answering this chemical challenge in her role as a photoresist chemist and as group leader at Bell

Laboratories (where she continues to use chemistry to empower electronic innovations as director of the Materials Research Department). The approach taken by Reichmanis was a design effort that explicitly used the existing photoresist knowledge base to associate each desired characteristic for the new material with a particular "molecular characteristic." A property like the desired radiation response was associated with one set of molecular characteristics or chemistries, while factors like low cost were associated with another set.

The 193-nm photoresists had a much shorter path from initial design to introduction, requiring roughly six years. By the early 2000s these resists were widely used by the semiconductor industry as part of its mainstay lithography technology generation. Yet as Moore's law has continued to be realized by the silicon community, the chemical (and market) imperative for improved photoresists has continued in tandem. Reichmanis predicts both continuity and change for the new generations of lithography technology that lie ahead. On the continuity side of the balance sheet, she is convinced that the chemical imperative will continue and that the key to making the new technologies possible will be new materials. On the side of change, Reichmanis sees new kinds of materials challenges. Soon, she noted, the very size of the polymer molecules of the photoresist will become an important consideration in maintaining an adequate sharpness to line edges in the patterns for devices with features below 30 nm in size. A new consideration for photoresists will therefore be the size of the actual photoresist molecules. Looking out farther still, Reichmanis foresees that an even more radical change in device fabrication technology may be required. This change would be a shift from the traditional "subtractive" process of semiconductor manufacture—in which entire layers of materials are deposited and patterned and unwanted excess material is removed—to an "additive process" in which only the desired material is deposited on the substrate where and when it is needed. Should such a shift occur, it would represent another chemical and material challenge once again at the center of electronics technology.

Feeding the Curve: Flows of Materials and Innovation

In a fundamental sense the semiconductor industry is a chemical industry. For the manufacture of integrated circuits, the semiconductor industry employs chemical, physical, and mechanical processes to add or subtract materials from silicon wafers to fabricate intricate material structures possessing very particular electronic capabilities. While chemical processing lies at the core of the semiconductor industry, where this industry differs from the traditional chemical industry—what sets it apart as a distinct activity—is that a host of disciplines beyond chemistry are involved in the design of its end products. Chemistry, both as a corpus of specialized knowledge about materials and as a constellation of materials produced by industry, empowers the semiconductor industry in crucial ways. Through this strong symbiotic relationship with the semiconductor industry, the chemical industry itself has been transformed.

Raj Gupta is well positioned to comment on this transformation. He has spent the past three decades with the Rohm and Haas Company, most recently serving as the firm's chairman and CEO. Since the middle 1990s he led the development of Rohm and Haas' electronic materials business. Electronic materials have assumed an ever-more prominent focus for Rohm and Haas, a firm with roots in specialty chemicals, resins, and polymers, as epitomized by its most famous product, Plexiglas. Given his long involvement in a "traditional" chemical firm and his role in its development of electronic materials, Gupta judges that the electronics industry has already had a profound effect on the evolution of the chemical industry, "not small time, but big time."

In Gupta's experience, the electronics industry has had many different, though interrelated, effects on the chemical industry. Rohm and Haas offers a case study of the general changes that have swept the chemical industry. A new pace and new practices for innovation have emerged in the chemical domain as the semiconductor industry pushed its requirements upstream to its supporting realms. In Gupta's experience, Moore's law has required the chemical industry to move faster and smarter. Supporting this claim, Gupta reviewed in detail the many senses in which the electronics industry has transformed the chemical industry.

Perhaps the most apparent manifestation of this transformation has been the emergence of electronics as a large, new market for advanced materials produced by the chemical industry. The semiconductor industry is one customer for a variety of such advanced, high-value added, but relatively low production-volume materials. Among the electronic materials produced by the chemical industry for the semiconductor industry are photoresists, etchants, dopants, specialty gases, insulators, polishing slurries, and packaging materials. In addition to the range of electronic materials used by the semiconductor industry, other types of electronics firms require advanced materials to create their end-products. Rohm and Haas, for example, manufactures specialty polymeric materials used to create flat-panel, liquid crystal displays for electronic products.

The electronic materials business has grown rapidly, Gupta noted. In terms of sales, electronics materials represent an annual $30 billion business for the chemical industry. By comparison this volume is equivalent to the annual global market for all agricultural chemicals. The agrochemical market took over a century to reach the $30 billion level. Electronics materials achieved the same scale in less than half that time and have consistently sustained 10 percent annual growth. In the case of Rohm and Haas, Gupta explained, opportunities in photoresists, insulating materials, chemical-mechanical polishing consumables, electronic packaging, and circuit boards now account for approximately a third of the company's total sales. However, exploiting these opportunities has required a large investment in innovation. Electronic materials account for 40 percent of the company's global research and development budget.

Several factors contributed to the innovation-intensive nature of electronic materials as compared with traditional chemical products, Gupta said. One factor is the rapid rate of change in electronic materials. Keeping apace with the development of semiconductor technology following Moore's law implies that product cycles for electronic chemicals are much shorter than for traditional chemical products. Chemical firms have lost control of the product cycle for new electronic materials. They must keep up with Moore's law if they want to supply the market need. In contrast to more traditional chemical products over which the chemical industry had greater influence on the innovation and product cycle, the chemical imperatives in the case of electronic materials are increasingly explicitly set by the Semiconductor Industry Association in its continually updated technology roadmap. “They say what performance they need [for new electronic materials],” explained Gupta, “and by which date.” The chemical industry’s challenge in electronic materials is to meet these deadlines, rather than discerning, anticipating, or shaping customer needs. To capitalize on the business opportunity represented by electronic materials, the chemical industry has had to tune its efforts to an externally driven product cycle, delivering the right materials on time. To do so has required the chemical industry to make proportionally larger investments in research and development for electronic materials than for its more traditional products.

A second factor that has contributed to electronic materials’ status as an innovation-intensive market for the chemical industry is the nature of the relationship between the chemical industry and its customers in the electronics industry. In the electronics domain, Gupta noted, the chemical industry experiences intense and rapid feedback about its products from its customers. Not only has the semiconductor industry’s setting of explicit requirements and timetables for the development of new electronic materials increased the pace of innovation, but this pace has also led the semiconductor industry—and other electronics companies—to provide more rapid, detailed feedback to the chemical industry about the performance and quality of new electronic materials products. To respond in kind to this feedback and seize the great market opportunity, the chemical industry further increased its research and development expense and its innovative efforts in electronic materials.

Therefore, given the innovation-intensiveness of electronic materials, the chemical industry has faced a demanding economic equation: electronic materials are high “value-added” products, the cost of adding this value is substantial, and the total volume of materials that are sold are low, compared with many traditional chemical products. To derive profitability and competitiveness from this equation, the chemical industry has had to transform its practices of innovation. In short, the chemical industry needed to invest more in research and development for electronic materials and accelerate its research and development. This shift in focus had a ripple effect inside chemical firms. Other business and technical practices, from marketing to manufacturing scale-up, have required streamlining to prevent them from forming obstacles in the innovation cycle. The demands made by the electronic materials market have necessitated that chemical firms revamp their entire system for product development and delivery. The chemical industry had to refashion itself to more closely resemble its electronics industry customers.

To bring about this change, to move faster and more efficiently from design to product with much tighter product cycles, the chemical industry had to rely on information technology, the end-product of its electronics industry customers. Gupta noted that it has been through the increased adoption of computing technologies in the innovation process and in other business practices, such as supply logistics, that the chemical industry has been able to win profitability in the electronics materials market.

These innovation practices and the growing knowledge base on the electronic structure and behavior of materials driven by the electronics industry is leading the chemical industry to pursue new product avenues in the field of “smart materials.” Ranging from self-repairing coatings to materials that change their bulk properties and even to textile materials that perform electronic functions such as solar power generation, the chemical industry is pursuing smart materials that hold the potential to add another meaning to the phrase "electronic materials." For decades, Moore's law has described the pace of technological change for the electronics industry. The chemical industry had to transform itself so that the electronics industry could realize its developmental curve. This transformation not only promises the continuation of Moore's law, in which the materials challenges will escalate, but also a new generation of innovative materials fusing the chemical with the electronic.

MANUFACTURING THE FUTURE: REALIZING MOORE'S LAW

Moore's law is a description of human activity as well as a statement about the inherent possibilities of silicon semiconductor manufacturing technology. The law connects the work of people with the capabilities of silicon integrated circuit manufacturing through its focus on economics. It lays out a path of economically optimal technology development. Moore's law is different from a scientific law such as the conservation of energy or the law of gravitation. Moore's law is grounded in the ongoing efforts of technologists to push silicon integrated circuit manufacturing forward. Moore's law has not and will not happen of its own accord. It relies on large-scale efforts by technologists directed toward manufacturing the future that it describes. Four of the speakers at CHF's symposium cast light on this central, human dimension of Moore's law. Carver Mead recounted his efforts of the 1960s and 1970s to provide technical evidence for the future possibilities of silicon technology, to instill in the silicon community a belief in the long-term viability of Moore's law, and to motivate the silicon community to invest the effort required to make Moore's law a reality. Patrick Gelsinger reviewed the range and scale of the work that has been required to realize Moore's law in the domain of microprocessor manufacturing and the broad economic consequences of having done so. Rodney Brooks provided a view of how this emphatic future orientation, predicated on continual exponential change, is shaping the forefront of computer applications research. Lastly, AnnaLee Saxenian detailed ways in which the efforts of the technological community to manufacture the future following Moore's law have transformed the geography and organizational forms of industrial activity, and how the realization of Moore's law has reshaped the human effort directed toward continuing it.

Believing in the Future: Moore's and Murphy's Laws

Carver Mead is a prominent figure in contemporary electronics, having been a contributor to the unfolding of Moore's law across the past four decades. Mead's career has had a single institutional base for fifty years—the California Institute of Technology. He has made key contributions to the design of semiconductor devices and has trained several generations of undergraduate and graduate students at Caltech who became key contributors to the development of semiconductor science, technology, and industry. It should come as no surprise that in his reflections on the course of Moore's law, Mead focused on inspiration—on his work in the electronics community to foster a strong belief in the future of semiconductor technology itself and of the great rewards that would justify the Herculean efforts required to make Moore's law a reality.

Mead earned all his degrees—from the bachelor's to the doctorate—in electrical engineering from Caltech, and he joined its faculty in 1959. As a resident transistor electronics expert, Mead soon encountered a Caltech alumnus who had returned to the campus on a recruiting trip—Gordon Moore. The two semiconductor-oriented "Caltechers" impressed one another in their first meeting, leading to an ongoing professional and personal connection. During their first meeting, Moore supplied Mead with an envelope stuffed with transistors. Mead was then teaching a course in transistor electronics, but the high cost of transistors prevented Mead from having his students work on individual projects with transistors. Moore, as a leader of Fairchild Semiconductor, was able give Mead a huge supply of "cosmetic reject" transistors—those that functioned but could not be sold because of some minor flaw. Mead's students would be able to build actual projects using real transistors, and from Moore's perspective, they would be learning on Fairchild products to boot. Learning by doing with advanced electronics was a way for Mead to form, in his students, a confidence in their future in electronics and the future of electronics itself. Moore's supplying of Mead with important means for building a belief in the future became a leitmotif of their ongoing relationship.

Throughout the early 1960s Mead commuted weekly from Caltech in Southern California's Pasadena to Fairchild Semiconductor on Northern California's San Francisco Peninsula—the region that would come to be known as Silicon Valley a decade later. On these visits, Mead would spend an entire day at Fairchild Semiconductor working with members of its research and development laboratory. At day's end, Mead would meet with Moore, the head of the laboratory, for a "decompression" session. It was during one of these regular sessions in the middle 1960s—around the time of the original publication of Moore's law—that Moore pursued a line of questioning with Mead that would come to shape the latter's activities for several years. At this time Mead was studying the role of electron tunneling—a quantum mechanical effect—in transistors. Moore was aware of this work and asked Mead, "Doesn't electron tunneling limit how small we can make a transistor?" Mead replied, "It certainly would." At very small distances—like those in an extremely small futuristic transistor—electrons would jump across barriers, in effect causing parasitic currents that would ruin the operation of the transistor. To Mead's reply that electron tunneling would place a lower limit on the size of the transistor, Moore asked, "How small is that?"

For Mead, reflecting later on his long association with Moore, this was typical of Moore's thinking: "Every single question was absolutely obvious, and I hadn't thought at all about it." Moore's inquiry set Mead on a train of investigations that would lead Mead to become a traveling spokesperson for the future of microelectronics. The first step was Mead's consideration of Moore's central question: How small could you make a transistor? As Mead dove into the problem around 1967, he uncovered several "prophecies of doom" lurking in the semiconductor community. Typical of these prophecies was a belief that if one made devices significantly smaller and packed many of them into a single integrated circuit, the heat generated by the power consumption of the many small devices would heat the chip to the point where it would melt. But as Mead looked at the physical realities of shrinking devices, this and other prophecies did not seem right. He decided to launch his own inquiry with a simple first step. What would happen with the simplest form of scaling? Mead calculated what would happen if he were to scale down the physical dimensions of the device, scale down the voltages, and scale up the concentrations of dopants in the imagined devices so that the various layers of the device maintained the same size fractions as existing devices. In these calculations, the device kept the same proportions, just much smaller.

The results surprised him. Mead found that with such simple scaling, transistors would exhibit an increase in speed. But when combined in an integrated circuit, the power used per unit of area would remain constant. Put differently, the power used per unit of speed would improve as the *cube* of the scaling factor. The amount of energy needed to perform a computation would geometrically, exponentially reduce as the devices were made smaller. The smaller you went, the better things got. Mead reworked his calculations several times because his result was "obviously a violation of Murphy's law, big time." What Mead had calculated was that as integrated circuit producers increased the complexity of chips on the exponential path that Moore had laid out in 1965, shrinking the sizes of the transistors on the chips would result in an exponential improvement in their performance. By making transistors smaller and cramming more and more of them onto a single chip, electronics would not only become cheaper, they would also become better.

Unsurprisingly, when Mead presented these results in the late 1960s, the semiconductor community reacted with great skepticism. In technology, as in so many areas of human activity, one seldom encountered phenomena that consistently flew in the face of Murphy's law. However, as silicon practitioners investigated Mead's result on their own, others began to concur. By the late 1960s Mead had instilled in himself—and in a growing constellation of silicon technologists—a belief in the future of miniaturized electronics. Electronics would improve as you made them smaller, so the rewards would be commensurate with the efforts required to do so. However, Mead reasoned, he had not yet answered Moore's original challenge. Transistors would get better as you made them smaller, but how small could you go? How long would this promising future last? Mead would soon argue that this promising future based on the continuing violation of Murphy's law would last for decades, with great returns reaped from following Moore's law.

In 1972 Mead, along with his graduate student Bruce Hoeneisen, had articulated a more formal answer and published it in a series of two papers.[3] Mead and Hoeneisen determined that there was nothing to prevent the construction of a workable transistor with features measured on the order of 0.15 microns—that is, fifteen hundredths of a millionth of a meter. As Mead recalled, at the time their proposition seemed "ridiculously" small. Transistors of the day had features measured in thousandths, rather than millionths of a meter, to say nothing of fractions of millionths. In the early 2000s, however, transistors with features at this very same 0.15-micron level had become the workhorse device for the semiconductor industry, and far smaller devices were planned for eventual mass production. But back in 1972 Mead coupled his ridiculously small lower limit for transistor size with a ridiculously large prediction for the resulting workable complexity of an integrated circuit—a single chip containing 10 million transistors. While Mead had succeeded in spreading a belief among the silicon community that a future of "smaller is better" was real, he encountered significant resistance to his papers of 1972. Many researchers had difficulty accepting that this future would last as long as Mead thought.

In response, Mead began what he today calls a personal crusade, a barnstorming crisscrossing of the country to "convince people that it really was possible to scale devices and get better performance and lower power" and that these possibilities had no immediate end in sight. As Mead recalled, an important aspect of his presentations to the silicon community was proof that not only were the benefits and future of scaling down devices possible, but that they were also actual. Mead presented evidence that the semiconductor industry was already in the process of realizing this future. To make his case, he turned to Moore. By this time, Moore had cofounded a new firm, Intel Corporation, which had introduced an impressive array of breakthrough semiconductor devices, including DRAM memories and the microprocessor. Over the years Moore had updated his plot of semiconductor complexity versus time that he originally published in 1965, adding new data points to his plot as Intel introduced new devices. His curve, his law, was holding fast. "Every time I'd go out on the road," Mead recalls, "I'd come to Gordon and get a new version of his plot." As Mead traveled throughout the silicon community in the early 1970s, he succeeded in building a belief in a long future for the technology, using Moore's plots as convincing evidence. In doing so, Mead also played a key role in fusing Moore's law with this belief in the future of electronics and building an expanding awareness of both. While Mead may not have been the originator of the phrase *Moore's law* (its precise origins remain murky), he undoubtedly acted as its charismatic Johnny Appleseed.

Today, four decades into Moore's law, Mead has seen the realization of his belief in the future and sees it extending further into the future. "For the past thirty years," Mead reflects, "we've basically made the same device and just made it smaller, and smaller, and smaller, and smaller without doing anything else." To make transistors smaller still from today's level, pushing beyond his 1972 limit of 0.15-micron devices down to the level of 10 nanometers, Mead sees the continuing importance of chemical innovation. New materials will be needed, but the promising future will continue.

As a prime example, Mead pointed to the effort to develop new, high dielectric constant insulating materials and to integrate them into semiconductor manufacturing processes. Up to the present, the natural oxide of silicon—silicon dioxide—has been used as the insulating material for microelectronics. The use of silicon oxide as an insulator has brought with it a classic trade-off that limits the miniaturization of devices. To have low gate current (a good thing), one needs a thin oxide layer. However, thin oxide layers increase the tunneling current (a bad thing). Replacing the insulating oxide with a new, specially engineered material will avoid this "either/or" dilemma, rendering it a "both/and" situation where size reduction can continue apace. Yet, Mead noted, such changes in materials will present, however rewarding, significant challenges: "It's no longer good old SiO_2. That means [the technological challenge] is harder because we were given a gift when an acceptable semiconductor has a fantastic insulator as its native oxide." That materials innovations are key to the continuation of Moore's law should come as no surprise given Mead's perspective: "It's a chemical process that makes integrated circuits, through and through."

Relentless Pursuits: Life at the Leading Edge

Intel's Patrick Gelsinger has spent his entire professional career at the leading edge of integrated circuit technology, advancing Moore's law. Gelsinger, a Stanford-trained electrical engineer, cut his silicon teeth on two important projects in the development of microprocessors—Intel's i286 and i386. These microprocessors, each a notable advance from its predecessor, helped to establish Intel's x86 microprocessor architecture as the dominant computer architecture of the past two and a half decades. Gelsinger was the chief designer of the highly successful i486 microprocessor, which led to his increasing responsibilities in the technological and business development of Intel's microprocessor franchise. He served as the first chief technology officer of Intel and is currently its senior vice president and general manager of the Digital Enterprise Group, where he continues to develop microprocessor and other silicon technologies for business computing and communications. During his two and a half decades with Intel, Moore's law has been a consistent presence for Gelsinger. Describing his long experience of living with Moore's law, Gelsinger said, "The relentless march continues on."

By at least one measure, this relentless march of Moore's law has led to a change of two orders of magnitude during Gelsinger's career alone. Since the original publication of Moore's law in 1965, transistor count (the number of transistors on a single integrated circuit) has served as a primary measurement of integrated circuit complexity and the power of semiconductor technology. In 1985 Intel introduced the 386 microprocessor for which Gelsinger had served as a key engineer. The 386 had a transistor count of 275,000, one hundred times the transistor count of Intel's first microprocessor from the early 1970s. Four years later in 1989, Intel launched the microprocessor for which Gelsinger served as chief architect, the 486. This was the first microprocessor to cross the 1 million mark in transistor count. A second order of magnitude increase in transistor count came in 2005, with Intel dual core microprocessors boasting 1.7 billion transistors on a single chip.

The great increase in computing power represented by the exponential growth in transistor count is equaled in importance by the closely related, second metric of Moore's law: the manufacturing cost of a transistor, Gelsinger underscored that as transistor count has grown by several orders of magnitude, the cost per transistor has dropped exponentially. From a cost point of tens of dollars for a single planar transistor circa 1960, in the early 2000s the semiconductor industry achieved a cost scale of nanodollars (billionths of a dollar) per transistor. This geometric cost reduction has been reached despite dramatic cost increases in semiconductor manufacturing. As the manufacturing cost of transistors has plummeted, the expenses of lithography, production equipment and building semiconductor factories or "fabs" have risen precipitously. However, Gelsinger noted, these manufacturing costs simply represent a capital investment challenge. What matters most is the continued realization of cost reductions per delivered transistor.

Gelsinger observed that it is precisely this cost reduction (as Moore foresaw in 1965) that has been the primary driver for the proliferation of electronics and their adoption across the globe and across social and economic sectors. This dissemination of electronics, propelled by the continued cost reduction, has had dramatic consequences in Gelsinger's perspective. For example, the semiconductor industry has become an important economic entity in its own right. In the early 2000s, it was a $200 billion industry (as measured by annual sales). Moreover, the semiconductor industry was the basis for an even larger economic sector, the information technology industry, which by this same time had become a $1.2 trillion global industry.

According to Gelsinger, the impact of Moore's law has been greatly amplified through the adoption of semiconductor electronics by other segments of the economy. The semiconductor industry, Gelsinger noted, is on its own a relatively small contributor to the gross domestic product (GDP) of the United States, approximately 3 percent. However, the industry has had an order of magnitude impact on economic productivity gains, with every element of GDP touched by the adoption of semiconductor electronics. The automotive, entertainment, financial, retail, and manufacturing sectors have all been transformed by the exponential decrease in the cost of semiconductor electronics.

For an illustration of these transformations, Gelsinger focused on the communications sector. It took an entire century for the communications industry to place one billion phone lines in service. Since 1973, the communications industry has, in contrast, put three billion mobile phones into service. In three decades, then, through the adoption of semiconductor electronics, the communications industry has tripled the entire connectivity of the previous century of the telephone industry. The world has witnessed a shift from one sixth of its population being "connected" to one half.

To keep semiconductor electronics on the path of Moore's law of expanding transistor counts and falling costs, Gelsinger noted that the manufacturing technology has become increasingly complex. Reflecting the fundamental role of the transformation of materials in semiconductor manufacturing, Gelsinger suggested that a count of the number of chemical elements involved in the manufacturing process is a good gauge of the general complexity of the process. For example, in the past two decades this elemental count has nearly quadrupled. In the 1980s, a dozen chemical elements were used in the manufacturing process. In the early 2000s, fifty-one elements were used. Gelsinger summarized: "We have seen this explosion, this resurgence, of the criticality of understanding materials science and chemistry at the core of our processing technology."

Looking to the future, Gelsinger forecast that this elemental count will increase as the semiconductor industry continues is "relentless pursuit" of Moore's law. While silicon will continue to provide the basic "scaffolding" for this continued development, the semiconductor industry will need to bring more and richer chemical and materials properties into silicon to continue the developmental trend of exponential performance improvement and cost reduction. Gelsinger envisions a future point at which the electronics components industry will need to diverge significantly from the traditional silicon technology path to continue the developmental trend of Moore's law that the silicon technology itself made possible. Such divergences may include the supplanting of metal interconnection technology with new technologies based on carbon nanotubes or silicon photonics. New structures may be needed to replace or accompany the traditional transistor design. Materials other than silicon may be required for the basic starting substrate for new components. Nevertheless, the exigencies of continuing the performance and economic trends of Moore's law will drive these divergences from the core silicon technology.

The overwhelming impact of Moore's law in the arena of computing—microprocessors—has added computing performance as a new and crucial factor to the innovation goals and trends of microprocessor producers. As Gelsinger noted, there are two central dimensions of computing performance: speed and power. Speed performance is the amount of computing that a device delivers per unit of time. Power performance is the amount of computing that a device delivers per unit of energy consumption. For the past two decades of Moore's law speed performance dominated in the realm of microprocessors. The frequency of microprocessors—the number of instruction execution cycles per second—was continually increased. With the miniaturization inherent in Moore's law, microprocessors were packed with ever more devices so that a greater number of instructions could be executed in each cycle. The speed performance of computing greatly increased. There were more instructions executed in each cycle, and more cycles were squeezed into a single second. While this increase of speed performance was exponential, it lagged the doubling of microprocessor complexity according to Moore's law. For each doubling of complexity, a 1.6 or 1.7 gain in speed performance was realized. Within this developmental pattern, power performance exhibited an ominous trend. Squeezing more cycles into a single second to achieve greater computation per unit time was extremely energy intensive. Power consumption expanded exponentially.

In the early 2000s this power consumption problem, Gelsinger recounted, led microprocessor producers to refocus their attentions on power performance. This refocus precipitated, in Gelsinger's estimation, the greatest shift to date in microprocessor architecture: the shift to multiple cores. Simply put, multiple core microprocessor architecture involves the creation of multiple, coordinated computing engines on a single piece of silicon. Multiple cores allow the microprocessor to execute a greater number of instructions per cycle. Thus, the multiple core microprocessor has better power performance: it delivers the same amount of computation with reduced energy consumption. The practicability of this new multiple core architecture, Gelsinger highlighted, is predicated by Moore's law. Multiple core microprocessors require an enormous quantity of components to form the computing engines. In order to pack this quantity of components into an area of silicon that can be manufactured with suitably economic yields, continued miniaturization of components will be required, in keeping with Moore's law.

To illustrate this connection, Gelsinger discussed the connection between the number of cores planned for future multiple core microprocessors and the planned new generations of semiconductor manufacturing technology. The semiconductor industry uses a nomenclature based on length to designate generations of manufacturing technology. This nomenclature reflects the fundamental place of miniaturization in the development of this technology. The measurement used is the silicon channel length in a transistor between the source and the drain—in other words, the length of the path that electricity takes in traversing a transistor. The current generation of dual core microprocessors is fabricated using a 65-nm manufacturing process. The next generation planned by the semiconductor industry, the 45-nm process, is predicted to afford microprocessors with four cores. The 32-nm process technology, planned for 2009, is anticipated to make eight core microprocessors a practicality. The future trajectory of microprocessor development has been planned according to Moore's law. The intent, Gelsinger said, is a revolution in the history of computing: in the multiple core era, the exponential growth of computing performance will overtake the exponential growth of device complexity described by Moore's law.

Riding the Tiger: Gearing Up for Exponentials

Rodney Brooks finds exponential developments like Moore's law in many areas of science and technology. Brooks is a noted robotics and artificial intelligence researcher, a founder of the robot manufacturer iRobot, and the director of MIT's Computer Science and Artificial Intelligence Laboratory (CSAIL). For Brooks, a range of factors cause exponentials in the development of science and technology: the level of adoption of a technology, the expectation of an exponential, and the cross transfer of an exponential from one domain into another. With the continuation of Moore's law predicted for at least the coming decade and a half, Brooks noted that computer technologists today face the challenge of preparing for this continuing exponential. Their challenge is to prepare to capitalize on the exponential expansion of computing power that is anticipated in the immediate future.

Brooks reviewed examples from MIT's CSAIL of how today's computer scientists are exploring computer applications that are presently computationally intensive—requiring hours or days to run on state-of-the-art computers. With the continuation of Moore's law and its rise of computing power and its lowering of cost, these applications could become widespread in our everyday lives. Brooks began with examples that could become commonplace given thirteen doublings of computing power. Thirteen doublings—assuming one doubling every two or three years on the trajectory of Moore's law—would constitute the length of a single technologist's career.

Brooks's first example was the generation of a three-dimensional model of an object from a single, two-dimensional digital photograph of it. Today, such an application requires hours of computation in order to perform reasonable inferences; for example, determining what the back of a building looks like from a photograph of its front. With thirteen doublings of computing power, such a task would only require several seconds. His second example was "motion magnification," where the dynamics of motion in a video clip is proportionally exaggerated, offering researchers "new ways of looking at the world." Again, while motion magnification requires hours of computation today, with thirteen doublings the process could occur in real time. Another of Brooks's examples was the use of video footage to build a model of the facial movements that an individual makes when speaking and then using this "synthetic" speaker to simulate the individual saying new dialog, singing new songs, and even speaking in different languages. With thirteen doublings, such simulation will require seconds instead of days, and the line between the "actual" and the "synthesized" will become even more difficult to discern.

In the arena of digital photography, Brooks noted, the changes that have already been anticipated by the continuation of Moore's law are profound and will have consequences that spill over into other technological domains. With the exponential growth in the number of pixels registered by the charged-coupled device (CCD) detectors in digital cameras, and the cost reduction in detectors pursuant to Moore's law, digital photography has largely replaced film photography. Today's challenge is how to best process all these pixels for display to the human eye. The challenge is to adapt display technology so that it can contend with an exponential increase in the power of digital photography described by Moore's law. For example, Brooks reviewed how researchers at CSAIL are investigating using computers to control an overlapping array of digital projectors to create ultrahigh-definition displays. By replacing mechanical precision of alignment and adjustment with computation, several doublings of computing power could render such a digital projector array as a path to future commonplace ultrahigh-resolution displays.

In the realm of microprocessor technology, Brooks forecasts that the continuation of Moore's law in the shift to multiple core architectures will push the effects of this exponential well beyond the bounds of semiconductor technology. He believes that the development of microprocessors with increasing numbers of cores will "change the whole structure" of computing. Software engineers and computer scientists will need to restructure their practices for creating software, and as they do, their practices will feed back into new designs of multiple core microprocessors: a reciprocal transfer of exponential effects circulating between hardware and software.

The exponential expansion of, and cost reduction for, data storage technology is closely coupled to the exponential of Moore's law for semiconductor devices. Brooks sees the effects of the continuation of Moore's law for data storage as having a profound impact on social life, in terms of the distribution of and access to information. Brooks presented his case using an evocative unit of "personal storage," the iPod. For the past several years there has been a doubling of storage every year on a $400 iPod, Brooks noted. Each year's new $400 iPod has twice the storage capacity of last year's model. If this trend continues, in just over ten years, an iPod could contain the text of all the books held by the Library of Congress. In twenty years a $400 iPod could store every movie ever made. This simple example shows the potential that continued technological potentials have to reshape our relationships with information, putting vast quantities of it instantly at our fingertips, says Brooks.

He noted the continued exponential development of what he calls the "silicon revolution" will change politics through redefining and expanding the list of major issues which society might address. The proliferation of sensor networks and wireless networks along with an exponentially increasing number of connected cameras in the environment will open up new possibilities for data mining and news reporting, along with enhanced security and privacy concerns. Similarly, an exponential increase in the amount of individual genetic information that is generated, stored, and used for identification purposes has the potential to change society with benefits of efficiency and security weighed against new forms of identity and privacy concerns. Continued geometric expansion of pure computing power, driven by Moore's law, could unlock new practices for data analysis and pattern recognition for scientists, technologists, and other researchers. Furthermore, this continued exponential in computing power could transform the human-machine interface through advanced, real time, voice and vision recognition as well as direct silicon-animal interfaces, that is, neural interfaces building on today's reality of hearing, vision, and motion control implants. As with any other dimension of human endeavor, Brooks noted, "that is the way of the silicon revolution: we are going to see things change in our lives. Some will be good. Some will be bad. We will have to work on what we want, and what we do not, and see where it leads."

Following the Law: Silicon Valley Goes Global

For AnnaLee Saxenian, Moore's law means more than the dramatic technological and economic changes wrought by the exponential development of semiconductor electronics. Saxenian, dean of information management and systems and professor of city and regional planning at the University of California, Berkeley, has studied the transformative effects of Moore's law on important social institutions: the way in which we organize work and companies, as well as the regional geography of industrial activity. As she noted, this dimension of social change brought about by Moore's law began with the transformation of Silicon Valley and has thereafter steadily gained a global scope.

The rise and development of Silicon Valley as an industrial region, distinctive for its system of business practices and organization, was spurred by three distinct technological waves: the integrated circuit wave of the 1960s and 1970s, the personal computer wave of the 1980s, and the Internet wave of the 1990s. In these successive waves of technological change, driven at their base by Moore's law, Saxenian said, the distinctive features of Silicon Valley as an industrial district were established. These features include a pervasive culture of entrepreneurial risk-taking and experimentation empowered by venture capital financing, the widespread adoption of specialization as a competitive strategy, high interfirm labor mobility and information exchange, and thriving community organizations (hobbyist clubs and engineering societies). These factors have facilitated the development of a local capacity for collective learning, adaptation, and technological dynamism that has brought the region such success, Saxenian concluded.

Nevertheless, Saxenian stressed, Silicon Valley possessed international features and connections from its earliest days. In the 1960s the Silicon Valley network extended to such countries as Malaysia and Singapore, to which the semiconductor industry increasingly shifted assembly operations, and to European countries, where Silicon Valley-based semiconductor firms established operations, subsidiaries, and joint ventures. Domestically, the Silicon Valley network grew to include semiconductor fabrication facilities in other states and a supply chain extending to the East Coast.

Though largely unrecognized, perhaps the most important dimension of Silicon Valley's global network in these decades was that of worker migration. The proportion of foreign-born workers in the United States' science and engineering workforce has grown steadily, so that by 2000 their proportion reached 38 percent. This percentage is even greater at higher degree-levels. Many of these foreign-born workers received their education in the United States, with the majority hailing from South and East Asia. Silicon Valley, Saxenian said, captured the lion's share of these foreign-born, U.S.-trained engineers. This "brain drain," from the perspective of the nations of South and East Asia, served as a crucial basis for Silicon Valley's professional labor supply, forming an essential, international component to the region's enabling network.

The story of this global network of labor migration, Saxenian pointed out, did not end there. Working in Silicon Valley, these foreign-born professionals learned how to be technologists, managers, and entrepreneurs. As a group these foreign-born professionals were more entrepreneurial than their domestic counterparts, as measured by the rate at which they started new firms. With the maturation of this community of Silicon Valley-based, foreign-born technologists, Saxenian observed, has come an important shift in the region's global orientation. In the past, Silicon Valley benefited from the "brain drain" from East and South Asia. Today, it is learning to live with "brain circulation" between the region and rising foreign centers of high-technology industry such as India, China, Taiwan, and South Korea.

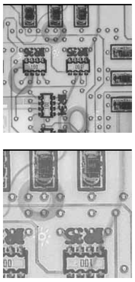
It is in this contemporary period of brain circulation—the migration of entrepreneurial technologists to Silicon Valley and then back to their home countries (sometimes in multiple iterations within a single career)—that Saxenian discerned a new pattern in the international expansion of the Silicon Valley network with the subsequent establishment of dynamic foreign centers of high-technology industry. She cited Taiwan and India as examples. In the 1980s Taiwanese technologists established Taiwan as the "foundry" extension of Silicon Valley. They established cutting-edge semiconductor manufacturing firms that produced integrated circuits designed by "fabless" Silicon Valley firms. This wave of success accelerated brain circulation of technologists from Silicon Valley back to Taiwan and the development of a specialized manufacturing infrastructure in the country along the lines of Silicon Valley. Today this Taiwanese activity has coalesced into an industrial district in its own right. While still connected to Silicon Valley, it has become more than just its appendage. Evidence for this shift, Saxenian noted, can be seen in Taiwanese firms' recent moves into Mainland China for manufacturing semiconductor devices and such consumer products as personal computers. Moreover, as was the case with Taiwan's development of an autonomous high-technology district though its relationship with Silicon Valley, the extensions of Taiwanese, Silicon Valley, and other networks into China are increasingly leading to the development of similarly connected, though autonomous, regional Chinese districts.

In Saxenian's estimation, the same pattern can be noted in the case of India. For design capacity, centers like Bangalore have increasingly become an important aspect of the Silicon Valley network. This success in semiconductor design and in software is accelerating brain circulation between Silicon Valley and India, leading to the development of increasingly autonomous high-technology districts across the country. In regions like Taiwan, India, and China, new firms are developing new products with adequate performance and cost features to serve the large potential market represented by the populations of these rapidly developing countries. For Saxenian, the consequences of both this brain circulation and the development of new high-technology industrial districts will generate some of the largest issues of the next decades.

Moore's law continues to change the face of technology and with it the economic geography of the world. In the years ahead the questions on everyone's lips will be: How fast will this dynamic spread to other parts of the world? How will new products and technologies begin to help the lives of residents of the developing world across Africa, Latin America, and other regions? What new applications and products will serve the needs of these new customers? The current state of affairs augurs a potential new exponential: the adoption of semiconductor electronics by a geometrically increasing proportion of the world's population. Fundamentally connected to Moore's law, the consequences of this new exponential for the future could be just as transformative and unforeseeable as it has been in the past.

ENDNOTES

1. For the complete program of the Moore's Law at 40 symposium, see pages 109–110 of this volume.
2. All of the quotations in this section, unless otherwise noted, are drawn from presentations made at the Moore's Law at 40 symposium. Transcriptions are archived at the Chemical Heritage Foundation, Philadelphia.
3. B. Hoeneisen and C. A. Mead, "Fundamental Limitations in Microelectronics—I. MOS Technology," *Solid State Electronics* 15:7 (July 1972): 819–829; B. Hoeneisen and C. A. Mead, "Limitations in Microelectronics—II. Bipolar Technology," *Solid State Electronics* 15:8 (August 1972): 891–897.



Program for CHF's Moore's Law at 40 Symposium

Thursday, 12 May 2005

6:00 p.m.	**The Age of Moore's Law: Cultural Perspectives, Societal Effects** Rodney Brooks

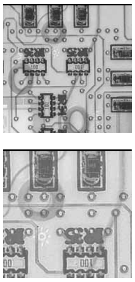
Friday, 13 May 2005

9:15–9:30 a.m.	**Opening Remarks** Arnold Thackray *President, Chemical Heritage Foundation*
9:30–10:00 a.m.	**Global Perspectives, Moore's Law, and the Semiconductor Industry** Patrick Gelsinger *Senior Vice President and General Manager, Digital Enterprise Group, Intel Corporation*
10:00–10:10 a.m.	**Questions and Discussion**
10:10–10:40 a.m.	**Chemistry and Moore's Law: From Shockley Semiconductor to Today** Harry Sello *Founder, Harry Sello and Associates*
10:40–10:50 a.m.	**Questions and Discussion**
	Break
11:20–11:50 a.m.	**Resists: Yesterday, Today, and Tomorrow** Elsa Reichmanis *Director, Materials Research, Bell Laboratories, Lucent Technologies*

11:50 A.M.–12:00 P.M.	**Questions and Discussion**
12:00–12:30 P.M.	**Electronics and the Evolution of the Chemical Industry** Raj L. Gupta *Chairman and CEO, Rohm and Haas*
12:30–12:40 P.M.	**Questions and Discussion**
12:40–2:00 P.M.	**Lunch**
2:00–2:30 P.M.	**Moore's Law and Electronics** Carver Mead *Gordon and Betty Moore Professor, Emeritus, California Institute of Technology*
2:30–2:40 P.M.	**Questions and Discussion**
2:40–3:10 P.M.	**Untold Stories of Moore's Law: Economics, Strategy, and Chemistry** Gordon Moore *Chairman Emeritus, Intel*
3:10–3:20 P.M.	**Questions and Discussion**
3:20–3:50 P.M.	**Regional Transformations: Industrial Districts** AnnaLee Saxenian *Dean, School of Information Management and Systems, University of California, Berkeley*
3:50–4:20 P.M.	**Break**
4:20–4:50 P.M.	**Panel Discussion**
4:50–5:00 P.M.	**Closing Remarks** Arnold Thackray

Moderators:

Miles P. Drake, *Vice President and Chief Technology Officer, Air Products and Chemicals*
Dennis Hess, *William W. LaRoche, Jr., Professor of Chemical and Biomolecular Engineering, School of Chemical Engineering, Georgia Institute of Technology*
Rob McCord, *Chairman, Eastern Technology Council*
Arnold Thackray, *President, Chemical Heritage Foundation*



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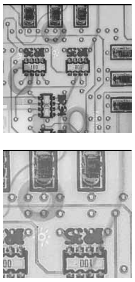

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