Intellectual and Economic Fuel for the Electronics Revolution

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The past three decades have witnessed revolutions in semiconductor electronics and in electronic computers. Progress in each has stimulated and directed the other. Today, the American semiconductor industry employs approximately 120,000 people, and the foreign semiconductor industry provides employment for another 150,000. But the true importance of semiconductor devices is not revealed by such numbers. Without these devices, the computer industry would not exist in its present form and size. Many electrical and electronic devices that we accept as commonplace today—such as the hand-held calculator and shirt-pocket radio—would probably not exist at all. In this article, we focus attention on semiconductor electronics, reviewing its evolution from a unique scientific base, showing how it served and was strengthened by space and defense missions, and pointing out the remarkable development of new enterprises and new teams that formed as the revolution spread. The point of looking back, of course, is to gain insight for moving ahead. We shall look ahead by expressing predictions and imperatives for the future based on the progress of the electronics revolution to this point.

Semiconductor Electronics: Its Beginnings and Development

At the end of World War II, there was significant interest in semiconductor rectifiers and in microwave diodes used as detectors and mixers. The dominant base for the imminent electronics revolution brought by semiconductors consisted of new developments in solid-state physics and technology.

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Solid-State Physics—An Open Scientific Base

The first paragraphs of Ralph Bown's foreword to Shockley's book (*1*) give an eloquent account of the scientific base for semiconductor technology:

> If there be any lingering doubts as to the wisdom of doing deeply fundamental research in an industrial laboratory, this book should dissipate them. Dr. Shockley's purpose has been to set down an account of the current understanding of semiconductors, an understanding which incidentally is comprised in no mean degree of his own personal contributions. But he has done more than this. He has furnished us with a documented object lesson. For in its scope and detail this work is obviously a product of the power and resourcefulness of the collaborative industrial group of talented physicists, chemists, metallurgists and engineers with whom he is associated. And it is an almost trite example of how research directed at basic understanding of materials and their behavior, 'pure' research if you will, sooner or later brings to the view of inventive minds engaged therein opportunities for producing valuable practical devices. The program of work which Dr. Shockley leads was aimed at understanding a kind of materials, the semiconductors, which had already received considerable application in the communications business in the form of rectifiers, regulators and modulators. Not only were improvements in such devices hoped for but the possibility of creating an amplifier was envisioned. In the course of three years of intensive effort the amplifier has been realized by the invention of the device named the transistor.

A set of fundamental developments came from the Bell Laboratories. Single-crystal germanium and silicon were first grown there; zone refinement to provide new orders of material purity was developed. Other firsts include the junction transistor, silicon-aluminum diodes, thermal-compression bonding of metals to semiconductors, impurity diffusion, and epitaxial growth of new layers on a seed crystal.

Open communication of the new science of semiconductors stimulated intense activity. The Bell Laboratories held symposiums to inform the scientific and technical community about these developments. Publications promptly disclosed new developments.

Inevitably, the gathering momentum of the semiconductor industry brought unparalleled career opportunities outside and new activities were nucleated in Dallas, Phoenix, and Mountain View. The authors, both alumni of Bell Laboratories, acknowledge the enormous and public-spirited contribution of the Bell Laboratories to semiconductor electronics in our American free-enterprise system.

Government Support of Semiconductor Electronics for Defense and Space

The importance of the transistor to defense electronics was immediately obvious. Army, Navy, and Air Force agencies immediately began the support of transistor electronics for the defense need. The pursuit of excellence was intense; competition developed among the various defense agencies to support the best ideas and the best teams in the various industrial laboratories and in the universities. Moreover, the commonality of interest among the contractors to the federal government promoted the high diffusion rate of new information in semiconductor electronics. The annual Device Research Conferences and the Philadelphia Solid-State Circuits Conferences were two forums for communication among the participants in the emerging field.

Governmental support of semiconductor R & D was large. From 1958 through 1974, various branches of the U.S. government pumped $930 million into research and development in the semiconductor industry. A very legitimate debate exists today as to whether government support of R & D in this industry has been as pivotal as the demand by military and space efforts for the devices manufactured by the industry. Very little objective data exist that can be used to support either side of this debate. However, it is our opinion that government support of university-operated research in this area was necessary in providing the atmosphere for training the brilliant students who then quickly found their places in the industry.

It is probable, however, that government-sponsored R & D in the industry itself was not as productive as the R & D which the industry chose to support itself. The reason for this is simply motivation. Government-sponsored R & D usually demands production of final devices

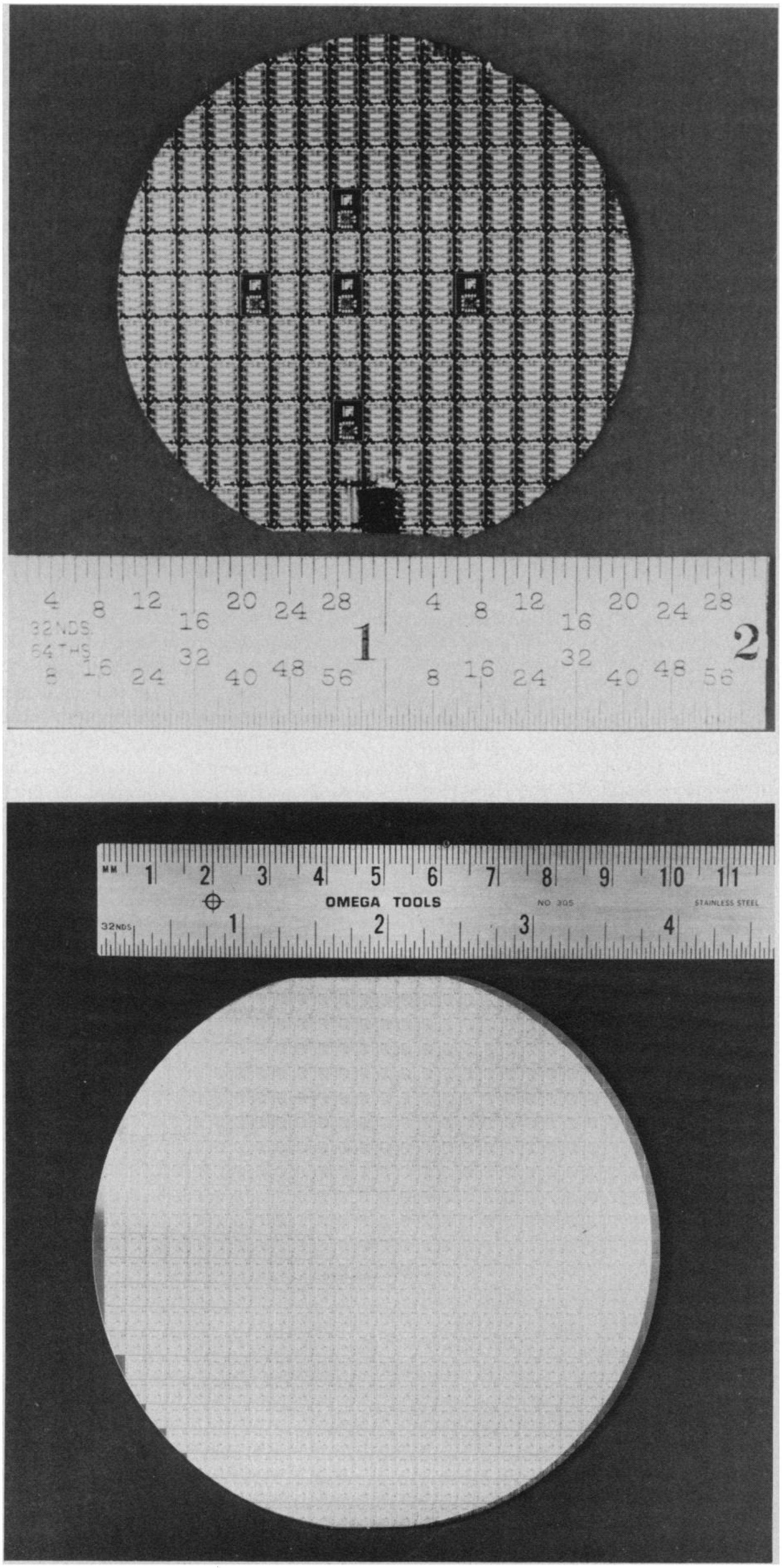


Fig. 1.(Top) Wafer manufactured in 1966; 1½ inches in diameter; 9000-square-mil dice; and 12-μm lines. (Bottom) Digital watch circuit; 4-inch wafer manufactured in 1976; 24,000 square-mil dice; 5-μm lines.

that might or might not be considered useful (that is, profitable) for the company involved. If the company chooses to sponsor R & D itself, then it is highly motivated to direct this R & D effort into products that it feels will be profitable to the company. In spite of this difference in motivation resulting in a difference in productivity, this $930 million provided useful effort that undoubtedly advanced the state of the art during its expenditure.

The U.S. Department of Commerce has published figures indicating that private industry supported $1.2 billion of R & D during the same period of time. So, all together, American industry was able to put more than $2 billion into R & D during this 16-year period. The total technical effort—including applications engineering, technical marketing, process control, and production areas—probably raises the investment that brought this industry into being between 1955 and 1975 to at least $3 billion.

In addition to R & D expenditures by the U.S. government, another important component of governmental support was contracts for production preparedness. Very early in the history of the transistor, the U.S. Army, Air Force, and Navy supplied capital dollars to the American semiconductor industry to build production equipment in order to have a capability to produce these new devices. The first such dollars were supplied in 1952 so that our industry could build production lines to manufacture alloy transistors.

While many companies were willing to support R & D efforts in this exciting new technology in 1952, few would have had the courage to build multimillion-dollar production lines at such an early date. This expenditure would have required the approval of the board of directors of the companies involved, and even if they had the foresight at that early time to begin production, their approval would have introduced a delay of at least several months. With the funds available from the U.S. government, an enterprising manager could build a production line without the approval and perhaps even without the knowledge of his board of directors.

As early as 1952 many American companies were motivated to build production lines for alloy transistors. Those who did found the business profitable. They got an early jump on their competitors who were still justifying this daring move. This technology diffused as rapidly through the United States as did R & D knowledge. Even though this initial investment by the U.S. government to build alloy transistor lines amounted to only $11 million, it provided a critical time advantage.

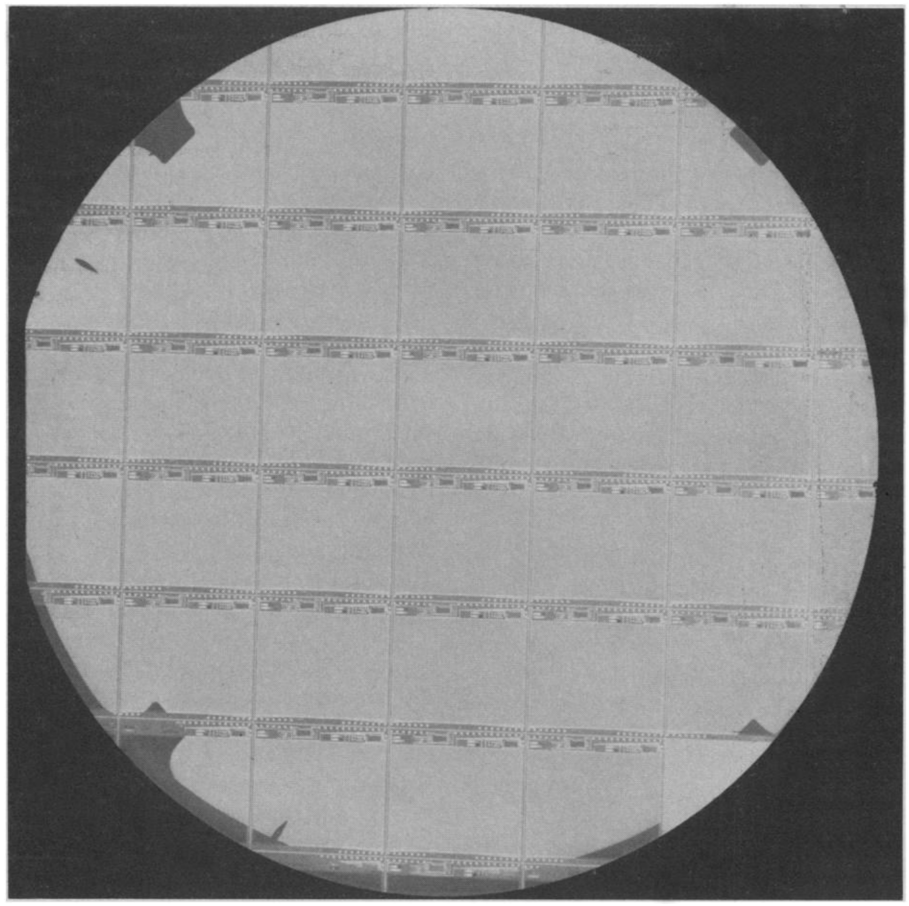
In 1957, the U.S. government provided another $15 million to industry to buy capital equipment to build production lines for diffused-base transistors. Again, while this amount was small compared to the money that private industry had to put up, it nevertheless gave an initial stimulus. As early as 1959, the services supplied another $10 million to American industry to buy or build the equipment necessary to build a production capability for integrated circuits.

Now, it is true that the $36 million supplied by the U.S. government in these contracts is a fraction of what our industry had to supply itself in order to build the enormous production capability that we now have. Nonetheless, the U.S. Signal Corps and Air Force, in particular, deserve credit for the foresight that they had so early in the game which led them to supply these needed capital dollars.

Many Americans argue that a large majority of the companies that got this early production support do not now exist as semiconductor suppliers and, hence, that the money was wasted. This is nonsense. Two of the largest recipients of the U.S. government support in the early days were Texas Instruments and Motorola. They did survive, and this early help was critical in helping them to an early start in the business. As for the companies that received support and failed, other successful companies hired their people and American industry was automatically farther along on the production learning curve because of the investment.

The largest markets in semiconductor electronics from the invention of the transistor through the middle 1960's were the computer industry and the military-aerospace industry. Two customers, because of their use volume, were absolutely pivotal in the early establishment of American semiconductor firms.

The first was IBM. In 1960, IBM was probably the largest single customer of every American semiconductor company. The second major customer was the Minuteman missile system. This missile system poured hundreds of millions of dollars into the semiconductor industry at a very important time in its history. This money went into diffused transistors and integrated circuits; in particular, it provided funds necessary for the refinements to achieve a high level of reliability for semiconductor devices. All



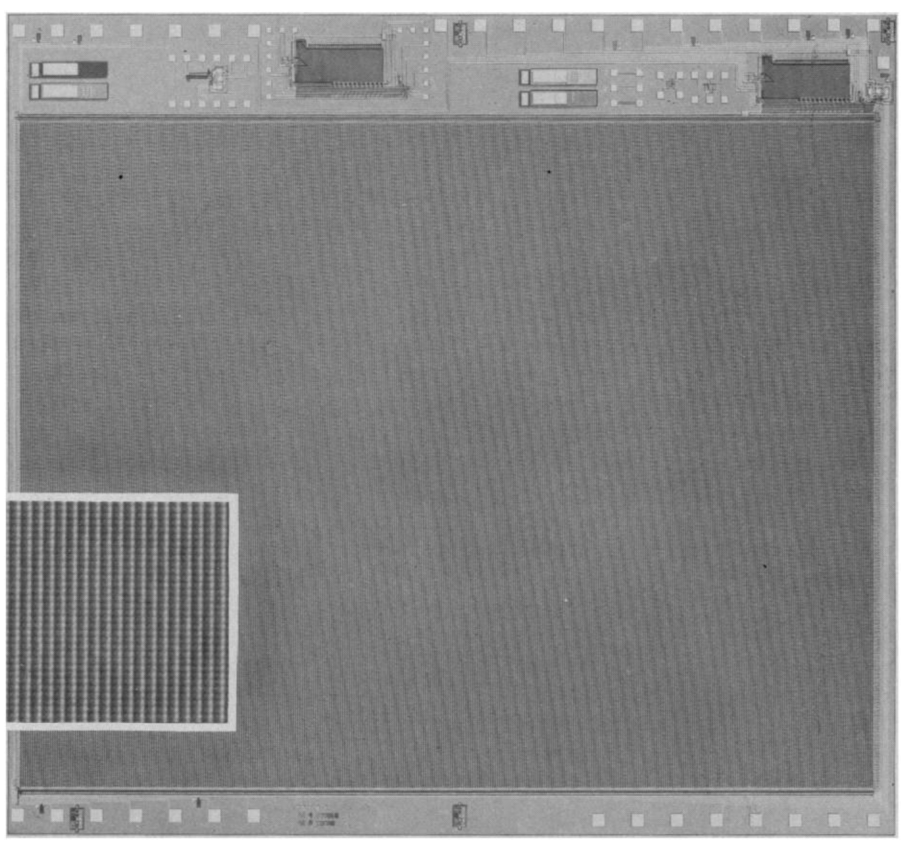


Fig. 2 (top). CCD imaging chip manufactured in 1976; 3-inch wafer. Fig. 3 (bottom). Individual CCD imaging die showing 4-μm structure.

subsequent semiconductor systems benefited from the technological advances with the new levels of electronic reliability.

Emergence of New Ventures

As electronics moved from the vacuum era to the semiconductor era, many observers expected that the industrial participants who dominated the vacuum tube component business would be the ones to establish leadership as semiconductor manufacturers. In 1955, the top ten American manufacturers of vacuum tubes in order of the worth of their sales were

RCA
Sylvania
General Electric
Raytheon
Westinghouse
Amperex
National Video
Rauland
Eimac
Lansdale Tube

The top ten American semiconductor manufacturers by sales volume in 1976 were

Texas Instruments
Motorola
Fairchild
National Semiconductor
RCA
Intel
ITT
Signetics
General Instruments
General Electric

Only two names appear on both lists. Clearly, the electronics industry in the United States exists within an economic and cultural system which not only spawned but actually encouraged the new order that was necessary for the proper winning of the vigorous new semiconductor market. The two key factors in this environment are the availability of venture capital and the mobility of American professional people. Vigorous young companies, with the motivation of partial ownership to their managers, have dominated the semiconductor industry. The American industry has been so successful that today it supplies approximately 75 percent of the world's integrated circuits.

Four separate market strategies have been successful in the development of new business connected with the semiconductor industry. The first strategy is market capture by price advantage in a widely used product. The leaders of the 1976 list (above) have all pursued this strategy with great success. They have exhibited remarkable capabilities to incorporate technological advances into their production to cut costs. They have responded rapidly to developing markets. Their performance has provided tremendous incentive to place electronic components throughout American industry in places where they had earlier been assessed as too expensive.

Some companies are of sufficient size to have sufficient internal markets for their products. Notable examples are the Bell system and IBM. Generally, the semiconductor devices produced for these internal, special markets contain similarities in some lines to the devices produced for commercial use by the large suppliers, but many devices are custom designed for the telephone and computer industries.

A third successful strategy is that of the instrument or system manufacturer which establishes and maintains semiconductor development and manufacturing capability for its internal use. The key idea here is to develop proprietary components that give the manufactured system an essential advantage over competitive systems. An outstanding case in point is Hewlett-Packard, which manufactures custom integrated circuits for its instruments, computers, and calculators. Intel, in its development of the microprocessor, exhibited a somewhat similar strategy. However, the microprocessor at this point is becoming a volume component of great importance.

The semiconductor industry, particularly on the San Francisco Peninsula, has generated a wide variety of small, successful companies which manufacture production equipment, materials, and components and provide services for the industry. Diffusion furnaces, ion implantation machines, epitaxial growth systems, mask-making systems, and others are all products of industries that are ancillary to semiconductor device production.

The Projection Forward

With the view of the dominant components of the development of the semiconductor industry to this point, we are in a better position to anticipate the developments ahead and to draw certain recommendations from them.

Centers of Action Ahead

A principal sector of the semiconductor industry is devoted to making potent microprocessors, memory chips, and standard linear circuits which can be used in enormous numbers. The last decade has seen a dramatic move from small-scale integration to large-scale integration. This change is illustrated in Fig. 1 (top) which shows a photograph of a wafer made in 1966–67 with individual dice 9000 square mils in area and having 12-micrometer lines on a wafer of 1½ inches. Below it is a photograph of a 4-inch wafer containing 5-μm lines on 24,300-square-mil dice of a 1976 digital watch circuit. Figures 2 and 3 are photographs of a wafer and die for a charge controlled device (CCD) imaging chip. The wafer is 3 inches in diameter, with each die having an area of 200,000 square mils and containing 180,000 imaging elements and 180,000 shifting elements.

There has been a great increase in the market share of integrated circuits. One decade ago, 86 percent of the sales of semiconductor manufacturers were discrete devices and only 14 percent consisted of integrated circuits. These circuits were very simple by today's standards. The most complex circuits of that time were dual J-K flip-flops with less than 25 transistors interconnected on one chip. In 1976, the share of total semiconductor sales attributed to integrated circuits had risen to 58 percent. Today, the state of the art is 16-bit microprocessors and 16,000-bit memories with approximately 1000 times the complexity of the devices built in 1966. The price for the 16,000-bit memory chip today is approximately the same as the price of a J-K flip-flop in 1966.

Both the staggering increase in complexity and the drastic reduction in cost have had a dramatic impact on the nature of the semiconductor business. In order to keep up with the rapidly decreasing prices, the industry has been forced to go from 1-inch wafers to 2-inch, then 3-inch, finally arriving today at the industry's standard 4-inch wafer. The diffusion furnaces have become larger, more accurate in temperature and gas-flow control, and much more complex.

In 1966, diffusion furnaces cost approximately $3000 per tube. Today, they cost $12,000 per tube. Today, a single mask aligner costs $50,000, an evaporator costs $80,000, 4-inch crystal growers cost $210,000, an epitaxial reactor costs $185,000. Each of these numbers is between a factor of 4 and a factor of 20 more expensive than typical equipment costs one decade ago. Ion implant equipment costs range between $100,000 and $300,000, depending on the flexibility required by the manufacturer.

Very new electron beam mask-making equipment requires a capital expenditure of $1.5 million for one electron beam machine. A typical wafer fabrication production area in 1976 uses four times as much deionized water per square foot of factory space as it did in 1966; it uses four times as much electric power.

Some of the increase in costs of equipment between 1966 and today has been due to inflation, but most of the increase has been due to the fact that increased size of the wafers and complexity of circuits being built have demanded larger pieces of equipment with much more exquisite control. To be sure, today's diffusion furnaces turn out ten times as many square inches of silicon as did the cheaper models of a decade ago, but the sales value of the output of a furnace has not increased.

In 1966, a small semiconductor company could be started with an initial investment of less than $1 million. Today, a similar company would require a minimum of $6 million. The design time and cost to bring today's state-of-the-art devices (16-bit microprocessors and 16,000-bit memory chips) is at least ten times, and probably 20 times what it was to bring state-of-the-art devices to market in 1966. Thus, the pendulum has swung in the sector of industry that provides sophisticated large-scale integration (LSI) devices for a mass market to favor the large and well-entrenched companies.

Semiconductor technology has brought a rapid succession of more and more able components costing continually less. The digital system designer at present has as basic building blocks the integrated microprocessor and memory chip. The potency of these blocks is illustrated by Table 1, which compares the parameters of a Fairchild F8 microcomputer, pictured without its power supply in Fig. 4, with the ENIAC, the first electronic digital computer. A brief study reveals that, for about $100, a system designer can now incorporate into *any* system he wishes a contemporary ENIAC, 20 times faster and 10,000 times more reliable, and requiring 56,000 times less power and 1/300,000 as much space. But better integrated circuit components of the same nature are ahead in the immediate future. Electron beam lithography and, ultimately, electron beam processing on the wafer promise still more dense integrated circuits. If the industry remains on the curve of complexity plotted as a function of time given by "Moore's law" (*2*), it will achieve a complexity of 10 million interconnected components by 1985. These developments constitute the on-going evolution in semiconductor technology. What is its goal? When it is reached, will the electronics revolution cease?

Table 1. Comparison of parameters of ENIAC with the Fairchild 8 (F8) microprocessor. Abbreviations: CPU, central processing unit; TTY, teletype terminal; ROM, read only memory; RAM, random access memory.

Item	Parameter	ENIAC	F8*	Comments
1	Size	3,000 cubic feet	0.011 cubic feet	300,000 times smaller
2	Power consumption	140 kilowatts	2.5 watts	56,000 times less power
3	ROM	16K bits (relays and switches)	16K bits	Equal amount
4	RAM	1K bits (flip-flop accumulators)	8K bits	Eight times more RAM in F8
5	Clock rate	100 kilohertz	2 megahertz	20 times faster clock rate with F8
6	Transistors or tubes	18,000 tubes	20,000 transistors	About the same
7	Resistors	70,000	None	F8 uses active devices as resistors
8	Capacitors	10,000	2	5,000 times less
9	Relays and switches	7,500	None	
10	Add time	200 μsec (12 digits)	150 μsec (8 digits)	About the same
11	Mean time to failure	Hours	Years	More than 10,000 times as reliable
12	Weight	30 tons	< 1 pound	

*For comparison in this table, the F8 microcomputer is assumed to consist of one 3850-CPU, one 3856-PSU (2K bytes of ROM), eight 1K RAM packages, and the static memory interface chip 3853, plus teletype terminal interface circuitry.

Let us look to the ultimate goal in the evolution of components. That goal is the availability of (i) microprocessors of arbitrary speed and reliability, (ii) memories of as large capacity and of as small size as one could want, and (iii) operational amplifiers with no limit of open-loop gain, response speed, input impedance, and output conductance. Of course, at the goal the cost of the components should not be a hindrance to their use. But this limit of component evolution is not the end of the electronics revolution—the revolution in electronic systems just then begins in earnest. The systems engineer is challenged to conceive and design systems that exercise the potency of the component. Programming the flow of information and control signals through the system becomes a problem focus. Thus, an impending center of action in electronics is conception and design of new systems which harness more potent components to tasks earlier adjudged interesting but impractical to perform.

Increased attention must be focused on the parts of the system, the transducers, to which the perfected electronics part interfaces. These transducers—sensors, actuators, display devices—have typically not benefited from the orders of magnitude of improvement that have occurred in the purely electronic devices. Transducers are susceptible to improvement through the use of strategies which succeeded in purely electronic components. Broad understanding of solid-state science suggests improvement in transducers; light-emitting diodes and photodetectors are existing cases in point. Microfabrication technique—photochemical machining, for instance—is readily extended to transducers. The transducer area will certainly become an important center of action in electronics.

Thus, we see two centers of action due to achieve increasing importance ahead, the areas of electronic systems and the component-like area of transducers. Both of these represent a wide range of opportunity. In each, there are unique opportunities for the new entrepreneur in operations of high mobility and modest size.

The Continued Importance of the Entrepreneurial Sector

We have seen in the recent history of semiconductor electronics an important role for new ventures. A major part of the success of the electronics revolution has come from companies that did not exist at the end of World War II. An account of the development of new companies on the San Francisco Peninsula has been given by Bylinsky (*3*). A recent report (*4*) of the Commerce Technical Advisory Board points out that young, high-technology companies exhibit larger growth in sales and in jobs (42.5

and 40.7 percent per year over the period 1969 to 1974) than do older companies classed as either "innovative companies" or "mature companies." In the period between 1945 and 1974, the group of six "mature companies" studied exhibited annual average growth in sales of 7.8 percent and in jobs of 1.9 percent. The five "innovative companies" studied showed average annual growth of sales and jobs, respectively, as 16.5 percent and 10.8 percent. Thus, the importance of successful new ventures is clear both for the economy and job market as well as for the provision of new electronic systems.

The need for and benefits of profitability in new ventures are sometimes poorly understood. Appropriate profit levels benefit all sectors. An incentive is provided to entrepreneurs for their initiative. To the company, profits provide capital for expansion or for new products. To the customer, a profitable enterprise is necessary to sustained production and continued service. To the government, tax revenue is provided, and to the public, products are provided concurrently with the provision of more jobs.

An Expanding Role for Schools of Engineering and Science

Semiconductor and computer electronics are founded on an increasing depth of scientific base. Accordingly, new professionals require an increasing level of preparation. This situation automatically involves the university in a stronger way than was the case a few decades back.

The university has long been recognized as an effective location for basic research. The coupling of the research mission with graduate education produces some essential economies. Educated people and research are coproducts in the university. Knowledge research by its nature is speculative; moreover, predictions of the nature, placement, and timing of breakthroughs are uncertain at best. These uncertainties are much less troublesome in the graduate school environment than in industry. A negative result may bear practically the same educational value as a positive one if it contributes to knowledge. This is an essential economy as compared to industry, where all bets are placed on the research result.

While the synergistic relationship between education and basic research (or pure knowledge research) has long been recognized, at Stanford University a strong synergism has emerged between graduate education and applied research in integrated circuits. A research program in integrated circuits demands an advanced working technology to be most effective. At the same time, problems of great contemporary interest to industry are hazardous to undertake in the university. The small university team is exposed to difficult competition from much larger industry teams. At Stanford, interesting applications not yet of commercial interest have motivated successful and demanding work in custom integrated circuits. A reading aid for the blind and a series of medical instruments requiring custom integrated circuits have provided dissertation topics for more than 60 Ph.D. candidates.

Many collateral positive effects have emerged. An important liaison with the medical community has been established in which medical doctors participate with engineers in the development of new instruments of great importance to their research or practice. These in-

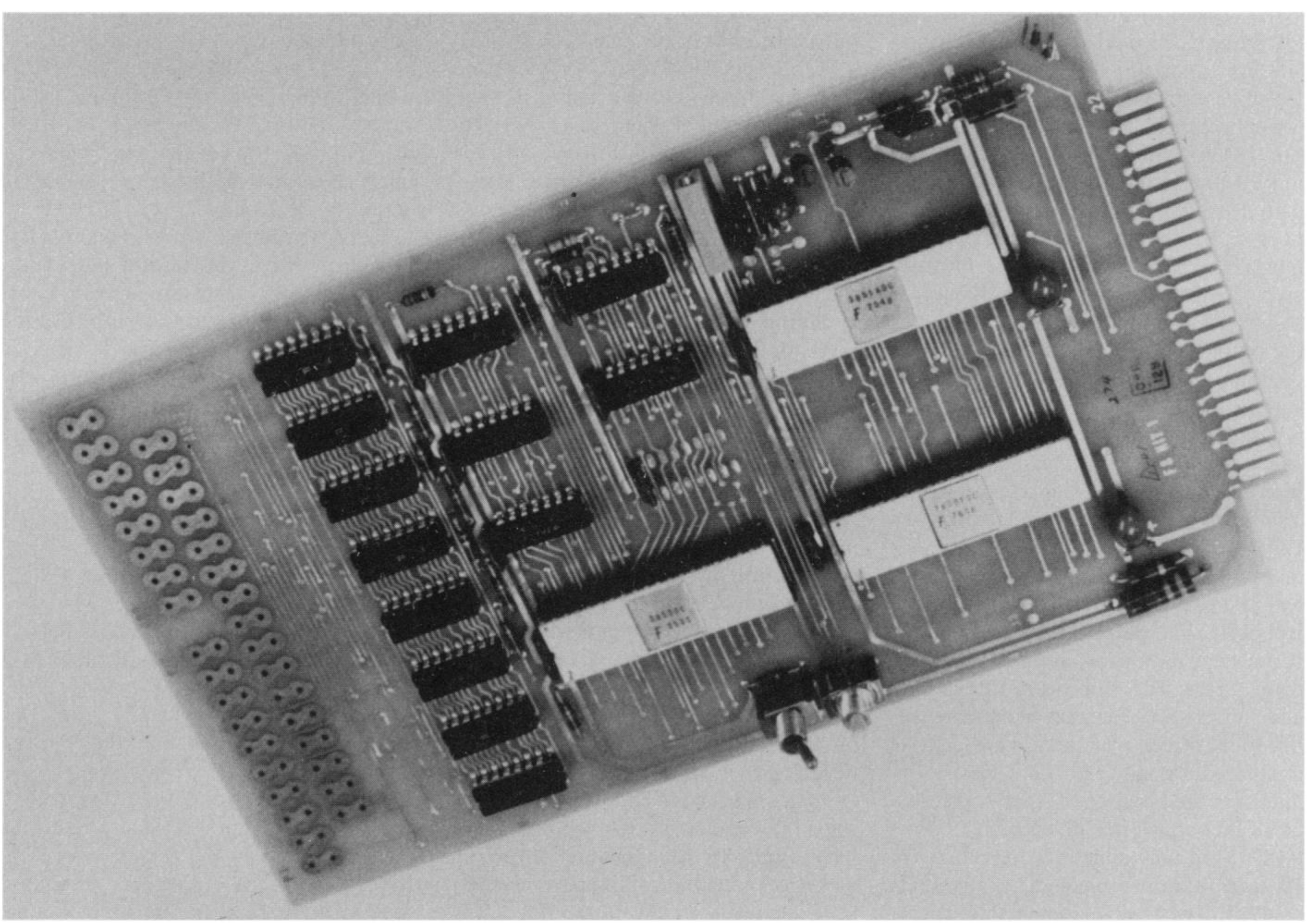


Fig. 4. The Fairchild F8 computer which is compared in Table 1 to the ENIAC.

struments (an ultrasonic imaging system, a series of blood-flow meters, new force transducers are examples) require custom integrated circuits which are the focus of study of graduate student teams. Liaison and collaboration with the integrated circuits industry has flourished. Industry has provided important inputs on contemporary technology. Early contact with promising candidates for employment has benefited both industry and the candidates. In one case, a new company was spawned to produce the blind reading aid using integrated circuits developed at Stanford. It has been profitably operating for 5 years with sales over the last year of $4 million.

From Our Crystal Ball

In the last quarter-century we have seen semiconductor electronics arise in the telecommunications industry and then provide the technological means to implement an emerging digital computer revolution, so that the individual today can personally own a more potent computational capability than his company or organization had then. Semiconductors have given the means to provide electrical power for space vehicles, to control their travel, and maintain their communication with the earth.

This electronics revolution has been fueled by a science base, promoted by government agencies vitally interested in the implements it promised, and carried out by new ventures with bold managers who perceived the opportunities and delivered outstanding performance. Electronics has grown in its utilization to address the urgent problems of defense and space, and its development from application to these problems has stimulated use in other areas. The $ 0.5-billion U.S. semiconductor business in 1960 was about half government and half private. By 1975, the $1.75-billion semiconductor industry had only a 22 percent government portion. We foresee that further development will proceed in the industrial and consumer sectors from the start already evident. We should like, however, to conclude with a forecast on the impact of electronics on the problem of this decade—the energy problem.

Semiconductor electronics will have a significant influence first in the area of energy conservation, in more efficient utilization of energy. Semiconductor high-energy ignition systems in vehicles are already improving efficiency. Microcomputer control of the variables of combustion (spark timing and fuel and air input) through measurement of engine temperatures and pressures and engine and vehicle speeds will make a further step in conserving fuel in transportation uses—uses that consume a quarter of our petroleum needs. In a similar way, more precise control of other systems that consume energy—heating, lighting, refrigeration, processing of food and material—can readily lead to economies not necessary with cheap fuel.

But, electronics also promises to bring power from renewable sources. We believe that photoelectric conversion of solar energy can be made viable as a source of power for terrestrial use within a decade. The harvesting of the average flow of 230 watts of solar power per square meter in the Southwest in significant quantities presents difficult problems. The necessary, large collection structures in a severe environment require a major capital outlay. The key to viability of solar energy is a sufficient conversion efficiency to support the capital outlay. An analysis (*5*) indicates that an overall conversion efficiency of 28 percent would produce power at the converter at 2 cents per kilowatt-hour. One method (*5*) with potential efficiency above this level is thermo-photo-voltaic (TVP) conversion. In TVP converters, silicon cells are irradiated by a 2000°K source heated by the sun. Silicon cells irradiated by a 2000°K source promise an efficiency greater than 40 percent if carrier lifetime can be kept as long as 1 millisecond. The processing of silicon cells at this point deteriorates the lifetime two orders of magnitude below the required value. We predict that perfection of photovoltaic converters can occur within a decade if sufficient effort is mounted to address the problem.

To us, this seems less remote than did the construction of components for Minuteman in 1958. At that point, a failure rate of 0.0007 percent per 1000 hours was required with a then-current failure rate for transistors of about 1 percent per 1000 hours. Actually, improvements were achieved in about 3 years and these reduced failure rates to about 0.0003 percent per 1000 hours.

The solar conversion program must be addressed with the same composite of forces that brought reliable components to Minuteman. Outstanding teams of engineers and scientists must attack the problems. The government agencies involved must exhibit the same vision of mission and persistent support of goal attainment. As viable designs emerge, production and installation must proceed with the same industrial competitiveness and efficiency that has characterized the past three decades of the electronics revolution.

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6. The authors dedicate this article to William Schockley to acknowledge his early and monumental contributions on which the electronics revolution is based. The contribution of J.G.L. to this article was supported by grant Eng-75-22329 from the National Science Foundation.