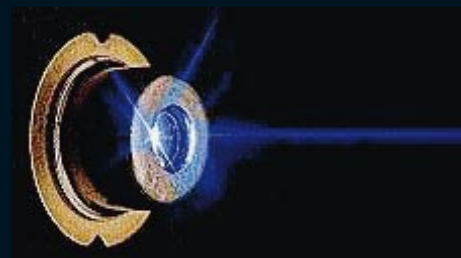
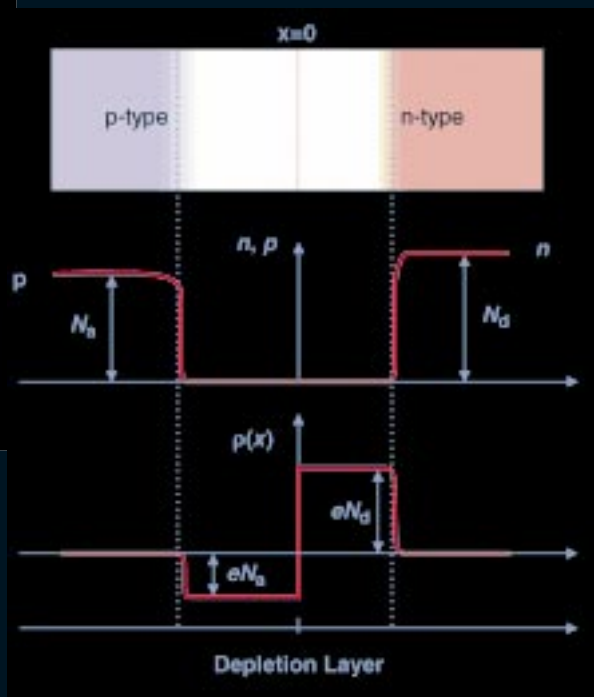


Integrated circuitry – the technology within our technology

The Nobel Prize in Physics 2000

Semiconductors – core to high speed optoelectronics



Turning Potential into Realities: The Invention of the Integrated Circuit (Nobel Lecture)**

Jack St. Clair Kilby*[a]

The integrated circuit, "the chip", led to microelectronics growing to become the basis of all modern technology, from powerful computers and processors, spaceprobes and medical diagnostic equipment through to washing machines and cars. The chip has also led to our environment being flooded with small electronic

devices, such as electronic watches and TV games. Here, the background and first steps in its development are described by its Nobel prize winning inventor.

KEYWORDS:

devices • electronics • germanium • semiconductors • silicon

The field of electronics had strong potential when I invented the integrated circuit in 1958. The reality of what people have done with integrated circuits has gone far beyond what anyone—including myself—imagined possible at the time.

Charles Townes won the Nobel for his work with laser technology, and he summed up how I feel. Townes said, "It's like the beaver told the rabbit as they stared at the Hoover Dam. 'No, I didn't build it myself. But it's based on an idea of mine!'"

At its most basic level, the integrated circuit manipulates the characteristics of electricity. In fact, the entire field of electronics is about manipulating the flow of electrons—in other words, making electricity perform advanced kinds of work. A long line of people have been involved in harnessing electricity, from William Gilbert, who first used the word "electricity" 400 years ago, to Thomas Edison who built one of the first practical electrical generators in the 1880s.

The invention of the vacuum tube, Figure 1, launched the electronics industry. Sometimes called "electron tubes", these devices controlled the flow of electrons in a vacuum. They initially were used to amplify signals for radio and other audio devices. This allowed broadcast radio to reach the masses in the



Figure 1. The vacuum tube controls the flow of electrons in a vacuum, which allows its use as an amplifier or switch; the latter application enabled the operation of the first digital computers.

1920s. Vacuum tubes steadily spread into other devices, and the first tube was used as a switch in calculating machines in 1939.

By the end of World War II, it was obvious that the cost, bulk, and reliability of vacuum tubes would limit commercial and military electronic systems. A naval destroyer built in 1937 had 60 vacuum tubes on board. Even the B-29, probably the most complex equipment used in the war, had only around 300 vacuum tubes. Most of those were single-function tubes.

Integration was a low priority at that point. However, electronic systems rapidly grew more complex. The post-war destroyers of 1952 had more than 3200 vacuum tubes. And, of course, the ENIAC computer of 1946 was a vacuum tube monster. It was the world's fastest computer for years, but it contained more than 17 000 vacuum tubes, weighed 26 tonnes, occupied 440 cubic meters, and consumed 174 kilowatts of electricity—equivalent to 233 horsepower.

Vacuum tubes clearly could not support any significant evolution of computers. People were able to visualize and design systems that—if realized with the prevailing technology—would be too big, too heavy, consume too much power, and simply get too hot to work. And because these components would have to be assembled from tens or hundreds of thousands of individual parts, they would have been unreliable and unaffordable.^[1]

By the mid-1950s, these problems were visible to many in the industry, and many researchers began seeking a solution. Military applications played a major role in the development of electronics. I think the Nobel Peace Prize is important, because it honors people who work to bring peace. And peace means we can use electronics to benefit mankind rather than wage war.

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Having said that, the early proponents of miniaturized electronic systems were the U.S. military and space agencies. Most of the approaches tended to make individual components smaller, so collectively these were called miniaturization programs. Each had a common objective—to build complete electronic circuits.

T. R. Reid has pointed out that building a circuit is like building a sentence.^[2] There are certain standard components—nouns, verbs, and adjectives in a sentence, and resistors, capacitors, transistors, and diodes in a circuit (Figure 2). Each has its own function. By connecting the components in different ways, you can get sentences or circuits that perform in different ways. Over the years, each component had developed a specialized set of manufacturing processes.

A huge step forward came in 1948, when Bell Labs unveiled the transistor. And in creating solid-state components, the race for miniaturized electronic circuits intensified.

Transistors rely on the nearly free travel of electrons through crystalline solids known as semiconductors. Semiconductors, such as silicon or germanium, have electrical properties that are

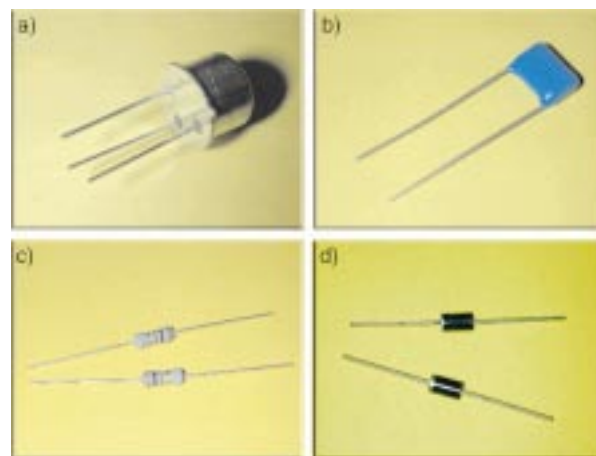


Figure 2. Components in a circuit include a) transistors, b) capacitors, c) resistors, and d) diodes.

between conductors and insulators. Not surprisingly, that's why they're called "semi" conductors.

We can change the electrical characteristics of semiconductors through a process called "doping," which carefully adds impurities to predetermined areas, Figure 3.^[3] Starting with pure silicon, one dopant will add electrons to a particular area. A different dopant will take electrons away to create holes in an area. In either case, we increase the conductivity of the basic material.

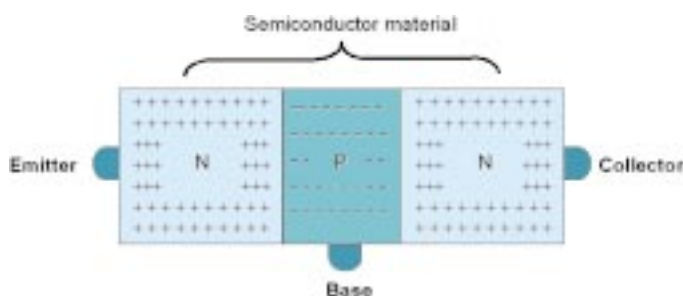


Figure 3. Doping of a semiconductive material—in this case forming an NPN transistor—will lead to a net increase in the number of electrons (n-type) or holes (p-type) in a particular area.

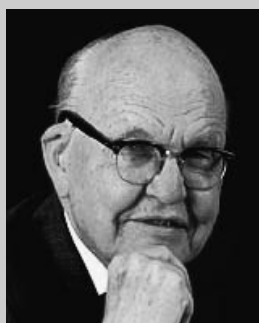
Semiconductor material that conducts by free electrons is known as n-type material. Semiconductors that conduct through electron deficiencies are called p-type materials. At its simplest level, a transistor is a "sandwich" of these materials, and the components are frequently encased in ceramic.

As with most technologies, the techniques for making transistors made steady progress. The first transistors were known as point contact. They were very primitive by subsequent standards but they did provide the initial breakthrough.

Later techniques included the grown-junction transistor (Figure 4) pictured here, and which will crop up again later in the lecture. In these transistors, a single crystal of germanium was grown and doped at the same time. The crystal was pulled from

Jack Kilby,

born November 8 1923, grew up in Great Bend, Kansas, USA. With B.S. and M.S. degrees in electrical engineering from the Universities of Illinois and Wisconsin, respectively, he began his career in 1947 with the Centralab Division of Globe Union Inc. in Milwaukee, developing ceramic-base, silk-screen circuits for consumer electronic products. In



1958, he joined Texas Instruments in Dallas. During the summer of that year he conceived and built the first electronic circuit in which all of the components, both active and passive, were fabricated in a single piece of semiconductor material half the size of a paper clip. He went on to pioneer military, industrial, and commercial applications of microchip technology. He headed teams that built both the first military system and the first computer incorporating integrated circuits. He later co-invented both the hand-held calculator and the thermal printer that was used in portable data terminals.

In 1970, he took a leave of absence from TI to work as an independent inventor. He explored, among other subjects, the use of silicon technology for generating electrical power from sunlight. From 1978 to 1984, he held the position of Distinguished Professor of Electrical Engineering at Texas A&M University. He officially retired from TI in the 1980s, but he has maintained a significant involvement with the company that continues to this day. In addition, he still consults, travels, and serves as a director on a few boards.

Jack Kilby is the recipient of the National Medal of Science (1970) and was inducted into the National Inventors Hall of Fame (1982). He holds over 60 U.S. patents.

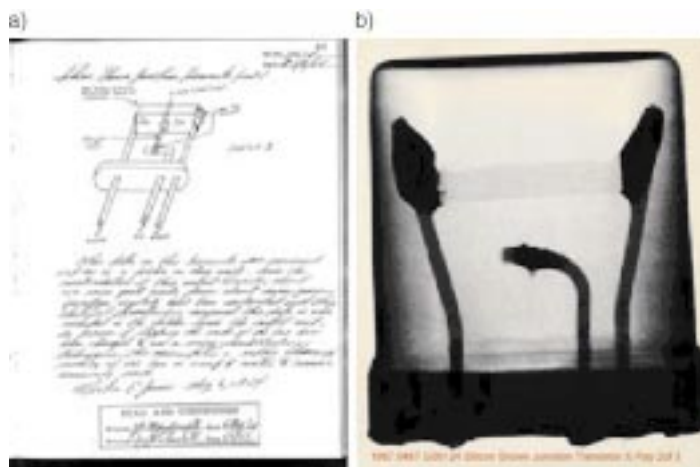


Figure 4. A grown-junction transistor as a) the notebook theory and b) an X-ray image of the device.

a melt containing n-type impurities, and then p-type impurities were added to the molten germanium. Later, more n-type was added. This created an n-doped crystal with a thin p-type layer within it. The crystal was then cut into small blocks, and each block formed a single NPN transistor. Subsequent developments included grown–diffused, alloy, surface barriers, and eventually the mesa and planar type transistors.

The earliest transistors were made from germanium. But silicon offered some big advantages in terms of much higher operating temperatures, breakdown voltage, and power-handling ability. The problem was that silicon was more difficult to refine because of its higher melting point.

Shortly before I joined Texas Instruments, that company solved the puzzle, making silicon transistors commercially available in the mid-1950s. But, I'm getting ahead of my story.

In 1947, I graduated from the University of Illinois with a degree in electrical engineering. That was one year before Bell Labs unveiled the transistor. That meant that I started my career at a very exciting time. But my formal training was in electrical power, though I had taken some vacuum-tube classes. Fortunately, I also had studied engineering physics, because I felt it might be more useful than knowing how to connect three-phase transformers! Looking back, I'm glad I took those physics classes.

I wanted to work in electronics, in part because of a childhood interest. My dad ran a power company that served a wide area in rural Kansas and he used amateur radio in his work. I found it very interesting. In fact, it was during an ice storm during my teens, when customers throughout his area lost power, that I first saw how radio—and by extension, electronics—could really impact people's lives, keeping them informed and connected, giving them hope.

After graduation, I was hired by Centralab, a Milwaukee-based electronics manufacturer. They made parts for radios, televisions, and hearing aids. Centralab was a fortunate choice for me, because they worked with hybrid circuits—an early form of miniaturization.

Centralab also developed what would become known as thick-film hybrid circuits. In this process, silver paint was

deposited on a ceramic substrate—or base layer—to form conductors. Carbon-based inks formed resistors. Small capacitors were formed in the substrate, and larger ones were attached. The necessary vacuum tubes could then be attached with sockets or soldered directly to the substrate.^[4]

Centralab was ideal for me in another way. The group I worked in was small, so I saw the entire process, from engineering through sales and production. My initial duties included the design and product engineering work on hearing aid amplifiers and resistor–capacitor networks for television sets.

Since it was a new field, making inventions was easy. Almost anything that departed from previous designs was novel and probably could be patented. In this period, I received about a dozen patents, the most notable being a capacitor design using the first reduced titanates and a technique for automatically adjusting resistors using sandblasting.

In 1951, Bell Labs held their first transistor symposium and began licensing transistor technology for a \$25 000 fee. At this time, Centralab became interested in making transistors and acquired a license. I felt the transistor pointed the way to the future and I wanted to be there. After some home study and some formal training that included Bell Labs symposia, I became the leader of a three-man project to build transistors and incorporate them into Centralab products.

We built a reduction furnace, crystal puller, and zone refiner. This was relatively complex at the time, but growing semiconductor crystals is similar in principle to the crystal-growing kit you might buy for a child today. We used our new equipment to make germanium alloy devices. We mounted unprotected transistors in a plastic carrier, which was a novel design. Environmental protection was achieved by using the ceramic substrate as part of the hermetic seal.

By 1957, Centralab had established a small production facility that sold small quantities of amplifiers for hearing aids and some other applications. They were even marginally profitable. It was clear, however, that major expenditures would soon be required, especially for the military market that was becoming a major opportunity. The military required silicon devices, which added to the necessary capital expense.

By 1958, I had decided to leave and began looking for another job. I talked with several companies and found that IBM had committed to technology similar to the thick-film work I had done at Centralab. I felt they had made a basic mistake by choosing a substrate that was much too small. Motorola was quite interested and thought I could work part-time on my own ideas about miniaturization. Texas Instruments was more enthusiastic than the others and offered me a job working in miniaturization full-time.

When I started at TI in May of 1958, I had no vacation coming that year. So I worked through the period when about 90 percent of the workforce took what we called "mass vacation". I was left with my thoughts and imagination.^[5]

I already had reviewed the earlier attempts at miniaturization. The vast majority of existing transistors held no potential for integration since their electrodes were on different surfaces—offering no realistic possibility of interconnecting them. Not that someone didn't try.

In the early 1950s, the Englishman Geoff Dummer of the Royal Radar Establishment suggested that all electronics could be made as a single block. He mentioned the use of amplifying layers, resistive layers, and things of that sort. The electrical functions would be connected directly by cutting out areas of the various layers.^[6] It was a remarkable statement. But Dummer gave no proposal for how to do it.

In 1956, Dummer gave a small contract to a British manufacturer to build such a device. They were completely unsuccessful, partly because they worked with the grown-junction technology I mentioned earlier and tried to connect the various layers.

While his device failed, Dummer was on target in general. The body resistance of the semiconductor itself—and the capacitance of the junctions between the positive and negative regions that could be created within it—could be combined with transistors to make a complete circuit out of the same material. My contribution was taking this idea and making it a practical reality.

While my first duties at TI were not precisely defined, I was free to choose an approach in the general area of miniaturization. The company made transistors, resistors, and capacitors. Since the company could make semiconductors cost-effectively, I thought it would be worthwhile to try and make everything from semiconductors.

This was contrary to most other major efforts at the time, which fell into three basic categories: One group felt the main problem was the assembly of individual parts, and that by making all parts the same size and shape, they could automate the assembly process. A second group thought that thin films were the way to go—a more modern form of the thick-film technology used at Centralab. Both of these approaches would have used conventional transistors and assembled them to the other components. A third group felt a more radical approach must be taken. They felt that our knowledge of materials was now complete enough so that entirely new structures could be invented to perform circuit functions. A quartz crystal, which performed the functions of an inductor and capacitor, was the favorite example.^[7]

It was clear to me that one of the major problems with all of the existing approaches to microminiaturization was that they involved different materials and fabrication processes. I began to consider an approach that would reduce the number of both.

It was obvious that transistors and diodes could be made of semiconductor materials. Discrete—or stand-alone—resistors and capacitors could also be made from semiconductors. However, that would be relatively expensive, and neither would perform as well as the best ones made with more conventional techniques and materials. For example, titanium nitride was better for resistors, and Teflon made better capacitors. Even so, since all components *could* be made with a single kind of material, it was possible to consider making them all within a single *piece* of material. By connecting them properly, complete circuits could be formed.

On July 24, 1958, I described in my lab notebook what would come to be known as "The Monolithic Idea". It stated that circuit

elements such as resistors, capacitors, distributed capacitors, and transistors—if all made of the same material—could be included in a single chip.

I quickly sketched a proposed design for a flip-flop circuit using components all made from silicon, Figure 5a. Resistors were provided by the bulk resistance in the silicon, and capacitors were formed at the PN junctions.^[8] I showed the design to my direct supervisor, Willis Adcock, upon his return from vacation. He was enthused, but skeptical. He asked for proof that circuits made entirely from semiconductors would work.

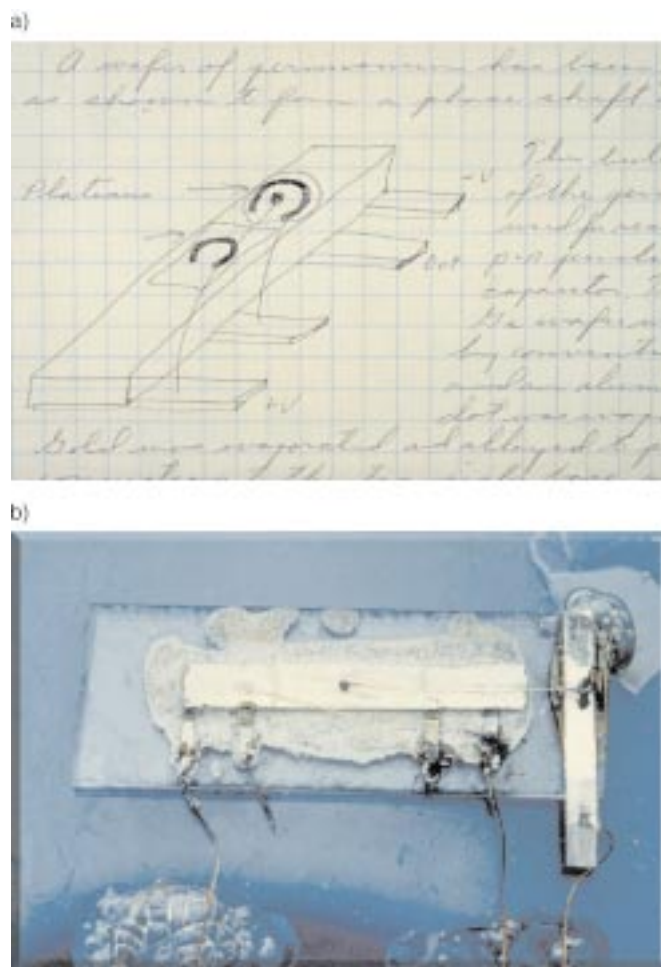


Figure 5. The first integrated circuit as a) the notebook theory and b) a photograph of the device.

Therefore, I built up a circuit using discrete—or separate—silicon elements, starting with packaged grown-junction transistors, Figure 5b. I formed resistors by cutting small bars of silicon and etching them to the required values. Meanwhile, capacitors were cut from diffused silicon power-transistor wafers, which had been metallized on both sides. Once assembled, the unit was demonstrated to Adcock on August 28, 1958. Fortunately, the test proved that all circuit elements could be built of semiconductor materials. But since I had used discrete components, it was not, of course, an integrated circuit. I immediately set out to build a truly integrated structure.

At the time, TI was very strong in grown-junction devices and had just begun to work seriously on diffused structures. One silicon transistor, a power device with an alloyed emitter, was in production. Several small-signal germanium devices also were in production. The emitter and base contacts were evaporated through metal masks. Mesas were etched after hand masking with black wax. I obtained several of these wafers, already diffused and with the contacts in place. By choosing the circuit, I was able to lay out two structures that would use the existing contacts on the wafers.

The first circuit attempted was a phase-shift oscillator, a favorite demonstration vehicle for linear circuits at the time. Technicians Pat Harbrecht and Tom Yeargan cut the wafers into bars about 3 by 10 millimeters. Metal tabs were alloyed to the back of the bar to provide contacts to the bulk resistors. Black wax was applied by hand to mask the mesas, one for the transistor, and a larger one for a diffused region forming a distributed resistor–capacitor network.

On September 12, 1958, the first three oscillators of this type were completed. When power was applied, the first unit oscillated at about 1.3 megahertz. To show that digital circuits could be built, the same techniques were used to build a flip–flop. That unit was completed on September 19.

By early October, we had begun designing a new germanium flip–flop integrated circuit. This unit was the first to be built entirely from scratch. It used bulk resistors, junction capacitors, and mesa transistors. The first working units were completed early in 1959 and were later used to publicly announce the “Solid Circuit” concept in March of 1959. Shortly thereafter, Robert Noyce of Fairchild Semiconductor showed the desirability of using the planar process with metal leads over the oxide, and several others, such as the folks from Westinghouse, contributed to the integrated circuit field.

Today, it is a little hard to believe, but in 1959 as we began to announce this idea—and Fairchild publicly discussed Noyce’s innovations—there was tremendous criticism. At the time, it was not obvious that the monolithic semiconductor approach was going to succeed over the others I outlined earlier. Gordon Moore, Noyce, a few others, and myself provided the technical entertainment at professional meetings for the next five years as we described and debated the merit of the various miniaturization systems.

There were three basic objections.^[9] The first was a belief that production yields would always be too low to be profitable. At the time, less than 10 percent of all transistors manufactured actually worked properly. Another group of people felt it did not make very good use of materials, since the best resistors and transistors were not made with semiconductors. Also, the true transistor people did not want to see their elegant devices messed up with all the other stuff on the chip. These arguments were difficult to counter, since they were basically true. And finally, many people working in the large companies thought if semiconductor technology succeeded, all of the world’s circuit designers would be out of work. Of course, employment of circuit designers has actually increased over the years, but they are doing their work differently than in the transistor era.

The turning point came from two highly visible military programs in the 1960s—the Apollo moon mission and the Minuteman missile. The adoption of integrated circuit technology by these programs was a strong endorsement.

By 1964, a few adventurous companies had begun docking integrated circuits into their commercial equipment. To help popularize integrated circuits, I participated in a TI team that developed the first handheld electronic calculator, Figure 6. Digital Equipment Corporation also was a very early user, and by the late 1960s, most engineers had accepted the fact that integrated circuits were here to stay. As the concept was accepted, hundreds and later thousands of the best engineers in the world began to work on it.



Figure 6. The first consumer application of integrated circuits: The handheld calculator.

My lecture has focused on the environment immediately preceding and following the invention of the integrated circuit. The innovation and development that has followed in the past 40 years has been more remarkable and far more rapid than all the developments in the prior 400 years after William Gilbert first coined the term “electricity”. Thanks to the work by hundreds of thousands of the world’s best engineers, we’ve not only created new applications for integrated circuits, we’ve also gotten much better at making them (Figure 7). New manufacturing processes have been devised, better transistors have been invented, and sophisticated techniques for computer-aided design have been developed. Consequently, progress in the field was rapid.

The early simple chips with a dozen components grew to chips with 10000 components by 1970, and more than a hundred million components today. This progress has been accompanied by a rapid decrease in the cost of electronic circuitry.^[10] In 1958, a single transistor cost about \$ 10. Today, you can buy a chip with over 100 million transistors for about that price, see Figure 8. Costs are almost certain to continue declining in the future. This decrease in cost of 100 million transistors to one has greatly expanded the field of electronics. Today,

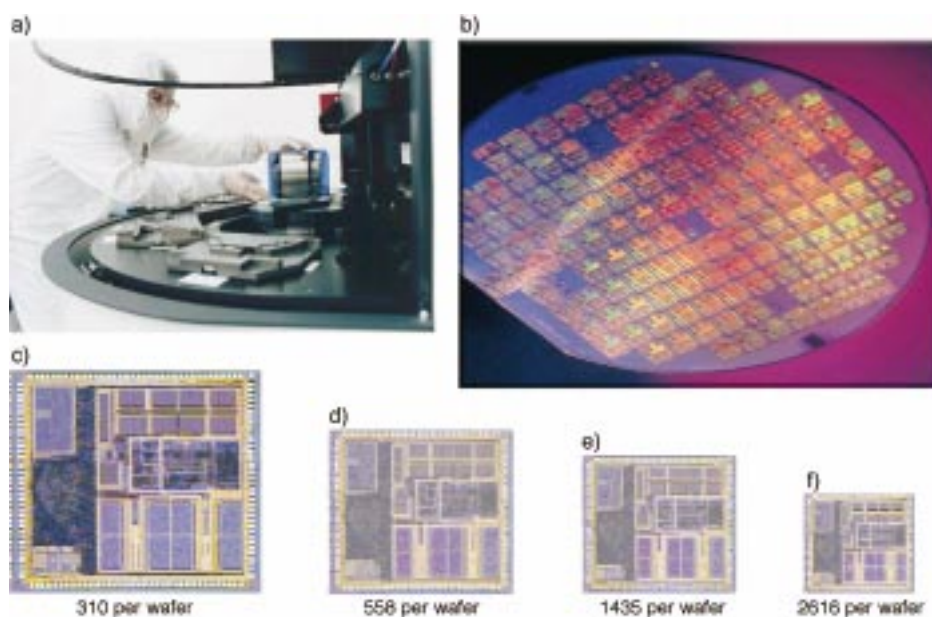


Figure 7. a) Under clean conditions, the IC is created on a silicon wafer; b) many such ICs are formed on one wafer. The number of ICs formed on a wafer increases with improved minaturization, from c) a 500 nm sized IC which allows only 310 to be formed per wafer, to d) 350 nm (558 per wafer), e) 250 nm (1435 per wafer), and f) 180 nm IC (2616 per wafer).

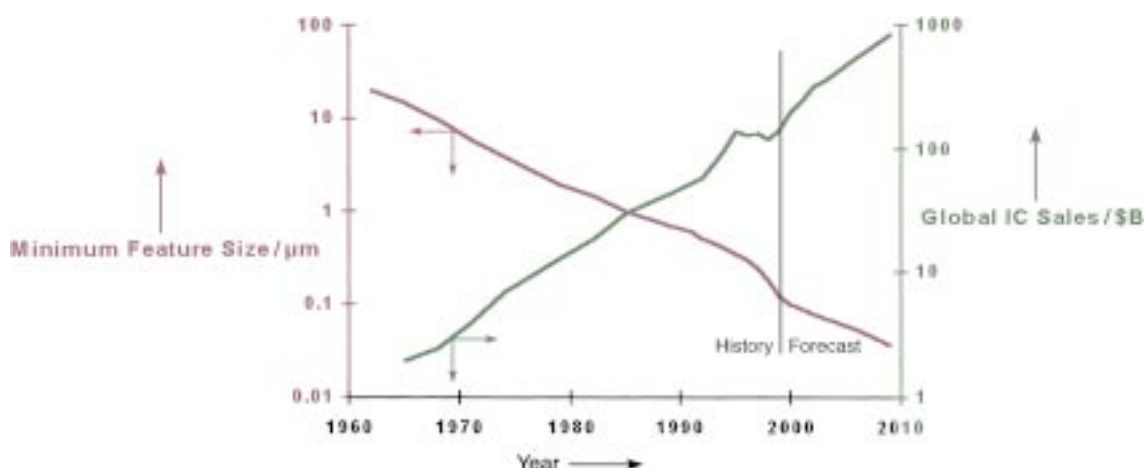


Figure 8. The minimum achievable feature size has progressively decreased with a commensurate lower cost per function of the chip, which in turn leads to a larger market for such products.

powerful personal computers sell for less than \$1 000; these are far more capable than the \$10 million versions of the 1960s.

While integrated circuits are used for military applications, many more are used to improve the quality of life for everyone.^[11] Automobiles are safer and emit fewer pollutants because of their integrated circuit systems. Radio and TV have become nearly universal, and hundreds of millions of people are united by the networking power of the Internet. Wireless communications keep people in contact with information and other people anywhere they go on the planet.

I believe the best is yet to come.

Today, approximately 1000 electrons are necessary to turn an individual transistor on or off. By 2010, it is estimated this will be accomplished by only 100 electrons. The 2010 projection assumes that higher dielectric constant materials will be

introduced. If they were not, then the continuation of geometrical scaling would extrapolate the reduction to a mere 10 electrons per transistor by 2010 and just one electron by 2020. That, of course, would present a fundamental physical limitation. Some proposed approaches around this obstacle include quantum-cellular automata and molecular switches, among others.^[12] When we reach this nanometer-length scale, many people think chemically assembled configurations will begin replacing today's patterned and etched structures.

I don't really know how all that will play out. I do know that engineers in all corners of the world continue to refine integrated circuits while others are working on what might come next. I know how they feel. In 1958, my goals were simple: To lower the cost, simplify the assembly, and make things smaller and more reliable. Although I do not consider myself responsible

for all of the activity that has followed, it has been very satisfying to witness the integrated circuit's evolution.

I am pleased to have had even a small part in helping turn the potential of human creativity into practical reality.

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