Chapter 1

THE CHANGING LANDSCAPE OF MICRO/NANOELECTRONICS

Since the first transistor was invented at Bell Laboratories in 1947, semiconductors rapidly evolved into a key enabler for providing solutions to societal, business, and consumer needs. In the past decades, the progresses of semiconductors are mainly powered by Moore's law focusing on IC miniaturization down to nanoscale, resulting in the transition from microelectronics into nanoelectronics.

Today, the semiconductor market has become the cornerstone of global high-tech economy, with more than 16% of the world economy built on semiconductors and with annual R&D budgets in the industry ranging up to 20% of revenue [1]. At the same time, semiconductors have become the cornerstone of modern society, and pervaded and penetrated in numerous aspects of human lives.

Recently, we have witnessed the quick development of a new area of Micro/nanoelectronics beyond the boundaries of Moore's law, called "More than Moore" (MtM). MtM creates and adds various nondigital functionalities to semiconductor products and focuses on creating high value micro/nanoelectronics systems, leading to virtually unlimited technology possibilities and application potentials.

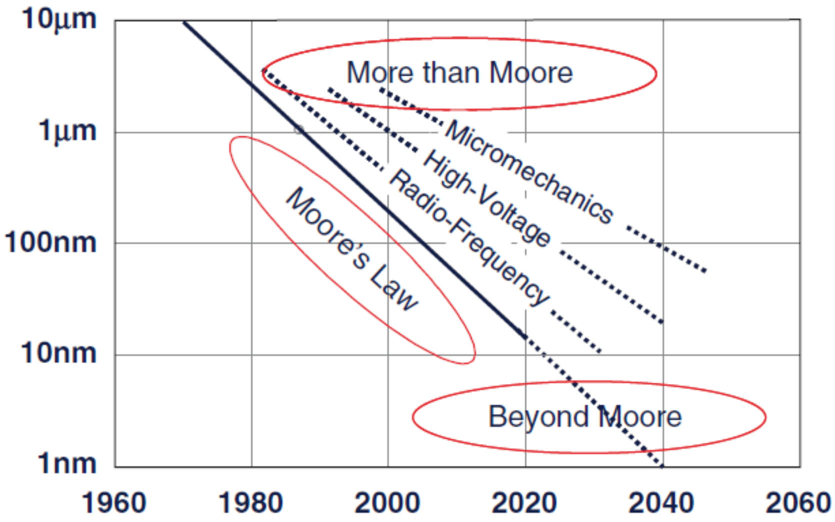


Fig. 1.1. Technology roadmap mirroring the European vision of the More-Than-Moore domain compared with More Moore and Beyond Moore (often referred to as Beyond CMOS)

Staying limited to "More Moore" or even "Beyond CMOS" thinking is probably not enough to secure a bright future. The recently proposed European "More-than-Moore" vision, in which functionality-enhancing special processes that do not necessarily scale with Moore's Law but nevertheless benefit from scaling where applicable are used to support a new system-level heterogeneous integration approach, is not only an attractive complementary approach but provides new opportunities for nanotechnology. Fig. 1.1 depicts the present European vision concerning the future evolution of the More Moore, More-than-Moore and Beyond CMOS domains [2]. Truly successful nanotechnology and nanodevices will precipitate a rupture in traditional ways of thinking and unify currently disconnected technology- and system-level design progress. The high level of innovation required will be facilitated by locking the designers of nanoscale devices, circuits and software together under the same roof to address strategic application domains. This is only possible by keeping expertise in the entire chain, from device through to system-level design and manufacturing.

1.1 TECHNOLOGY EVOLUTION

The story of the first transistor begins well before Bell Labs scientists first started working on developing such a device in the 1930s. It was scientists in the 1800s - including Maxwell, Hertz, and Faraday- who made the dramatic scientific discoveries that made it possible to harness electricity for human uses, while inventors applied this knowledge in the development of useful electrical devices like radio.

Wireless communication was born in 1895, when Marconi successfully sent a radio signal over a distance of more than a mile. But before the technology could be fully practical, better detectors needed to be developed to detect the radio signal carrying the information. Rectifying crystal detectors were eventually incorporated into radio receivers, which were able to separate the carrier wave from the part of the signal carrying the information. However, crystal sets only worked with strong radio waves, which tend to weaken over distance and terrestrial obstructions. Amplification was needed. English physicist John Ambrose Fleming provided the first step towards a solution with his invention of the rectifying vacuum tube: a lightbulb outfitted with two electrodes attached to radio receiving systems. The American inventor Lee DeForest added a further innovation: a third electrode, called a grid, consisting of a network of small wires surrounding the cathode, with a negative potential that controlled the flow of electrons from the cathode to the anode, producing an amplifying current.

The amplifying vacuum tube was not only an essential component in the development of radio, but also in early telephone equipment, television sets, and computers. But the technology was less than perfect. Vacuum tubes consumed too much power, gave off too much heat, took up too much space, cost too much to produce, and eventually burned out and needed to be replaced. These shortcomings prompted one Bell Labs engineer, J.R. Pierce, to proclaim, "Nature abhors the vacuum tube." [3]

In the 1930s, Bell Labs scientists were trying to use ultrahigh frequency waves for telephone communications, and needed a more reliable detection method than the vacuum tube, which proved incapable of picking up rapid vibrations. They reverted to a crystal-based detector, which worked effectively and set them on the path of exploring the particular properties of the most reliable semiconductor material: silicon. In the process, they discovered that silicon was comprised of two distinct regions, one favoring positive current flow ("P") and one favoring negative current flow ("N"). The discovery of this "P-N junction", and the ability to control its properties, laid the foundation for the transistor.

John Bardeen, Walter Brattain and William Shockley spearheaded the Bell Labs effort to develop a new means of amplification, speculating that by adding a third electrode to the semiconductor detector, they would be able to control the amount of current flowing through the silicon. The resulting device would, theoretically, amplify as well as the vacuum tube with much less power consumption and in a fraction of the space.

The research efforts peaked during the so-called "Miracle Month:" November 17 to December 23, 1947. Brattain had built a silicon contraption to study the behavior of electrons at the surface of a semiconductor, in hopes of discovering what was causing electrons to block amplification, but condensation kept forming on the silicon. To cope, Brattain immersed the entire experiment in water, inadvertently creating the largest amplification thus far observed. Informed of the result, Bardeen suggested making an amplifier in which a metal point was pushed into the silicon and surrounded by distilled water. The device worked, but the resulting amplification was slight.

But Bardeen and Brattain were encouraged, and doggedly began experimenting with different materials and set-ups, eventually deciding to replace the silicon with germanium. The result: amplification 330 times larger than before. Unfortunately, it only worked for currents with very low frequencies, while a phone line, for example, would need to handle all the complex frequencies of a person's voice.

The scientists decided to replace the liquid with a layer of germanium oxide. However, in the course of the experiment Brattain realized he'd accidentally washed off the oxide layer. Surprisingly, he was still able to achieve some voltage amplification, and he could achieve it at all frequencies. The gold contact was puncturing holes in the germanium which canceled out the obstructing effect of the surface electrons.

So the key components were a slab of germanium and two gold point contacts just fractions of a millimeter apart. With that in mind, Brattain placed a ribbon of gold foil around a plastic triangle, and sliced it through one of the points. When the point of the triangle was placed onto the germanium, the signal came in through one gold contact and increased as it raced out the other: it was the first point-contact transistor (Fig. 1.2).

At roughly half an inch high, the first transistor was huge by today's standards, when 7 million transistors can fit onto a single silicon chip. But it was the very first solid state device capable of doing the amplification work of a vacuum tube, earning Bardeen, Brattain and Shockley the Nobel Prize in Physics in 1956. More significantly, it spawned an entire industry and ushered in the Information Age, revolutionizing global society. This was perhaps the most important electronics event of the twentieth century.

With the advent of the transistor and the work in semiconductors generally, it seems now to be possible to envisage electronic equipment in a solid block with no connecting wires. The block may consist of layers of insulating, conducting, rectifying and amplifying materials, the electrical functions being connected by cutting out areas of the various layers [4].

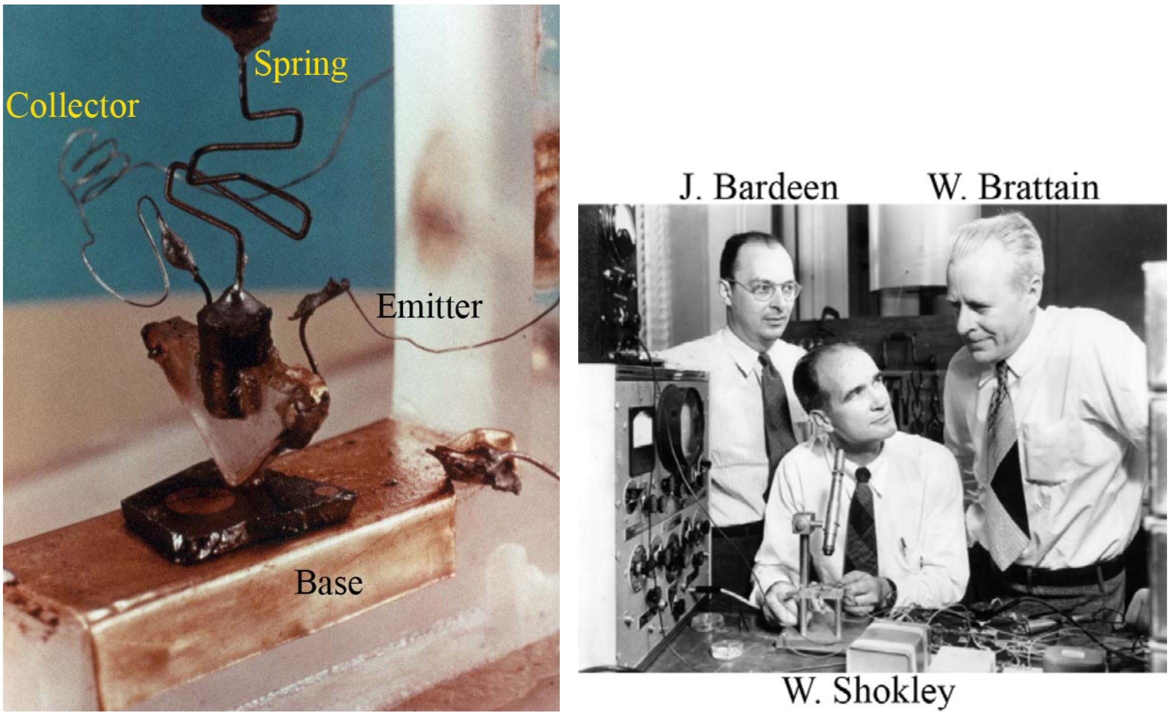


Fig. 1.2. The first point contact transistor and its inventors: William Shockfey, John Bardeen, and Walter Brattain, Bell Laboratories, Murray Hill, New Jersey (1947)

Early developments of the integrated circuit go back to 1949, when the German engineer Werner Jacobi (de) (Siemens AG) [5] filed a patent for an integrated-circuit-like semiconductor amplifying device showing five transistors on a common substrate in a 3-stage amplifier arrangement. Jacobi disclosed small and cheap hearing aids as typical industrial applications of his patent. An immediate commercial use of his patent has not been reported.

The creation of the integrated circuit was hindered by three fundamental problems, which were formulated by Wallmark in 1958 [5, 6]. The first problem was integration. In 1958, there was no way of forming many different electronic components in one semiconductor crystal. Alloying was not suited to the IC and the latest mesa technology had serious problems with reliability. The second one was isolation. There was no technology to electrically isolate components on one semiconductor crystal. And finally, it was connection. There was no effective way to create electrical connections between the components of an IC, except for the extremely expensive and time-consuming connection using gold wires.

It happened so that three different companies held the key patents to each of these problems. Sprague Electric Company decided not to develop ICs, Texas Instruments limited itself to an incomplete set of technologies, and only Fairchild Semiconductor combined all the techniques required for a commercial production of monolithic ICs.

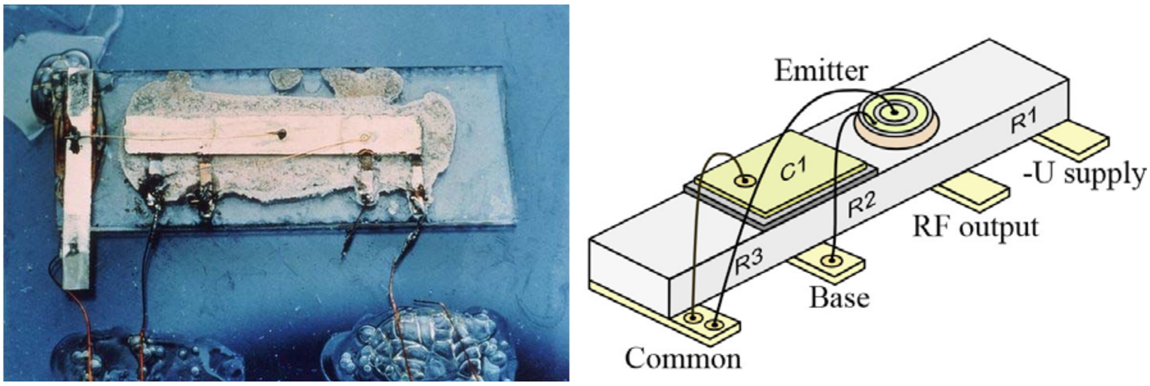
The main principles of integration were formulated by Jack Kilby who filed a series of US Patent applications in 1958–1959 [7]. As others at Texas Instruments and elsewhere were doing in 1958, Kilby looked at microminiaturization and made an assessment of the various government-funded projects then underway. Among those projects was one that Texas Instruments was already involved with, called Micro-

Module, which involved depositing components on a ceramic wafer. Kilby did not find this approach cost effective (although IBM chose a variation of it for its System/360). In the summer of 1958 he came up with a fresh approach – to make all the individual components, not just the transistors, out of germanium or silicon. That swam against the tide of prevailing economics in the electronics business, where resistors sold for pennies, and profits came from shaving a few tenths of a cent from their production cost. A resistor made of silicon had to cost a lot more than one made of carbon. But Kilby reasoned that if resistors and other components were made of the same material as the transistors, an entire circuit could be fashioned out of a single block of semiconductor material. Whatever increased costs there were for the individual components would be more than offset by not having to set up separate production, packaging, and wiring processes for each.

Jack Kilby built an ordinary circuit with all components, including its resistors and capacitor, made of silicon instead of the usual materials, in August, 1958. In September he built another circuit, only this time all the components were made from a single piece of material – a thin 1/16-inch x 7/16-inch wafer of germanium. (The company's abilities to work with silicon for this demonstration were not quite up to the task.) He and two technicians laboriously laid out and constructed the few components on the wafer and connected them to one another by fine gold wires. The result, an oscillator, worked (Fig. 1.3).

So, Kilby formulated three fundamental features of integration:

- the only thing that a semiconductor company can successfully produce is semiconductors;
- all circuit elements, including resistors and capacitors can be made of a semiconductor;
- all circuit components can be formed on one semiconductor crystal, adding only the interconnections.



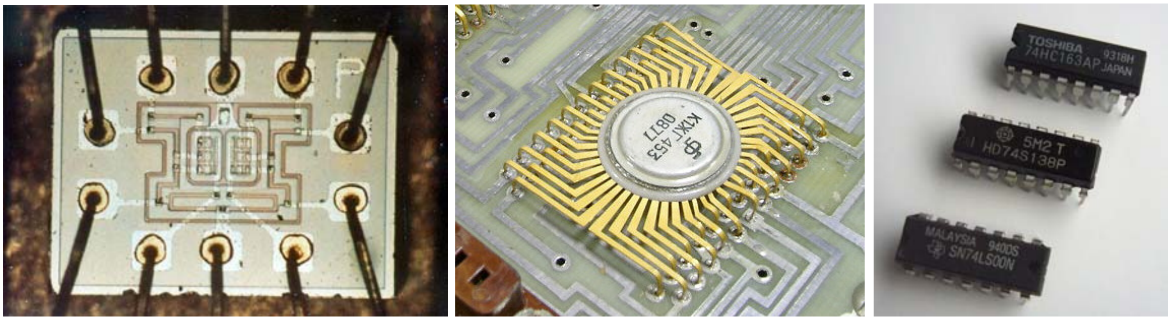
a *b*

Fig. 1.3. Kilby's original integrated circuit: view (a) and schematic (b)

The same idea was realized with silicon wafer. It was Robert Noyce from Fairchild Semiconductor (California) who in January 1959 described in his lab notebook a scheme for doing essentially the same thing Kilby had done, only with a piece of silicon [7]. One of his coworkers at Fairchild, Jean Hoerni, had paved the way by developing a process for making silicon transistors that was well-suited for photo-etching production techniques, making it possible to mass-produce ICs cheaply. It was called the "planar process," and as the name implies, it produced transistors that were flat. The process was best suited to silicon, where layers of silicon oxide – one of the best insulators – could be built up and used to isolate one device from another. The idea of using silicon oxide as an insulator solved another important problem – the problem of interconnections that hindered mass-production of ICs. The passivating oxide layer forms a natural barrier between the chip and the metallization layer.

Kilby also mentions the use of metallization layer. However, Kilby favored thick coating layers of different metals (aluminum, copper or antimony-doped gold) and silicon monoxide instead of the dioxide. These ideas were not adopted in the production of ICs.

In March 1961 Fairchild announced their first commercial IC series, named "Micrologic", and then spent a year on creating a family of logic ICs (Fig. 1.4) [5]. By that time ICs were already produced by their competitors. Texas Instruments abandoned the IC designs by Kilby and received a contract for a series of planar ICs for space satellites, and then for the ballistic missiles LGM-30 Minuteman. Whereas the ICs for the onboard computers of the spacecraft "Apollo" were designed by Fairchild. Each computer "Apollo" contained about 5000 standard logic ICs, and during their manufacture, the price for an IC dropped from US$1000 to US$20–30. In this way NASA and the Pentagon prepared the ground for the non-military IC market.



a *b* *c*

Fig. 1.4. Logical NOR IC from the computer that controlled the Apollo spacecraft (1), Russian IC (2), 74 series IC logic gates

As of today, the semiconductor market has become the cornerstone of global high-tech economy. At the same time, semiconductors have become the cornerstone of modern society, and pervaded human lives in the past 50 years. Without them, the rich multimedia experience that we enjoy in today's world of CD, MP3, DVD, and the Internet would not have been possible.

Without them, we would not be able to talk to people around the world, exchange messages, or share photographs and video clips via a personal portable device that fits into our pocket. Without them, our cars would do far fewer kilometers per liter of fuel, heavily pollute the environment, and cause more accidents. Gordon Moore estimated in 2003 that the number of transistors shipped in a year had reached about 10^{18}. That is about 100 times the number of ants estimated to be in the world. Semiconductors are with us everywhere and anytime.

The shift from the past era of microelectronics, where semiconductor devices were measured in microns (1 millionth of a meter) to the new era of nanoelectronics where they shrink to dimensions measured in nanometers (1 billionth of a meter) will make the semiconductor industry even more pervasive than it is today. It will allow much more intelligence and far greater interactivity to be built into many more everyday items around us, with the result that silicon chip technology will play a part in virtually every aspect of our lives, from personal health and traffic control to public security.

However, in the future, the semiconductor industry cannot be exclusively based on the same "business as usual" strategy. This is due to the facts that many aspects of the business, technology, design, and system level requirements are now simultaneously changing when approaching fundamental limits at the nanoscale. The introduction of new materials and technology steps, increased process variability, tough reliability need, are all impacting system level design at the same time, confronted with extremely large and complex architectures and quasi-impossible-to-solve power density issues. On the other hand, the applications will also be different. Consumers and society at large demand new types of electronics products with more than digital function, short-time-to-market for new product creation, and continuous cost reduction. This chapter intends to draw an overview picture of the changing global landscape of semiconductors by highlighting some of the major development trends, covering both technology and business.

1.2 MOORE’S LAW

On April 19, 1965, the Electronics Magazine published a paper by Gordon E. Moore [8] in which he made a prediction that the number of transistors on a chip roughly doubles every 2 years. The term "Moore's law" was coined around 1970 by professor Carver Mead from California Institute of Technology in reference to the paper [8]. Known as Moore's law, his prediction has enabled widespread proliferation of technology worldwide, and today has become shorthand for rapid technological change (Fig. 1.5).

Moore's law is about miniaturization, and about extreme miniaturization (Fig. 1.6). As one example, the Intel® 45-nm high-*k* metal gate silicon technology packs more than 400 million transistors for dual-core processors and more than 800 million for quad-core. Intel demonstrated 32-nm logic process with functional SRAM packing more than 1.9 billion transistors in 2009. The total length of the interconnect lines connecting different transistors of a single IC can be as long as several kilometers.

In 2011 Intel has deployed a fundamentally different technology for future microprocessor families: 3-D transistors manufactured at 22 nm [9]. These new transistors enable Intel to continue to relentlessly pursue Moore's Law and to ensure that the pace of technology advancement consumers expect can continue for years to come. Previously, transistors, the core of microprocessors, were 2-D (planar) devices. Intel's 3-D Tri-Gate transistor and the ability to manufacture it in high volume, mark a dramatic change in the fundamental structure of the computer chip.

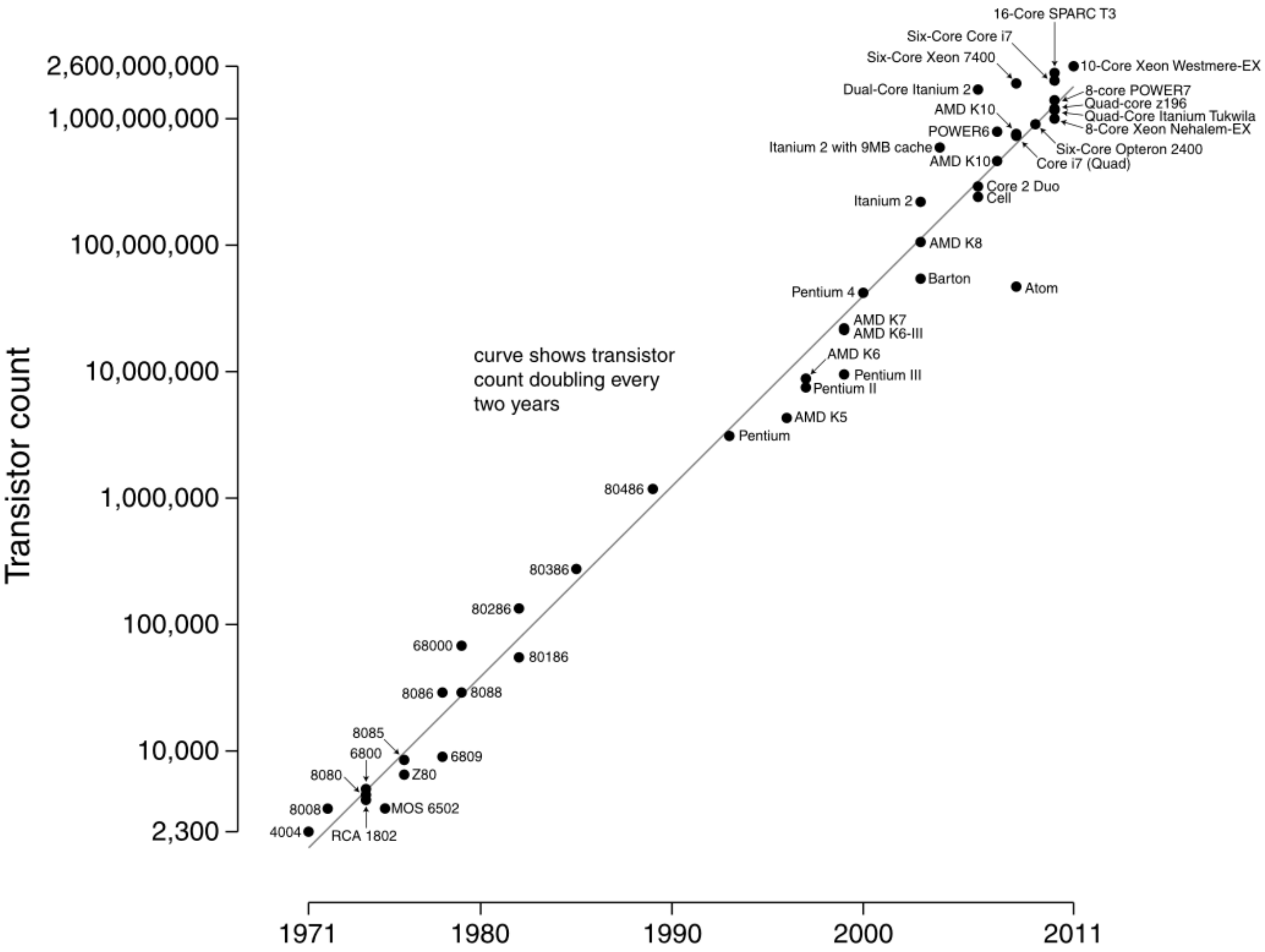


Fig. 1.5. Microprocessor Transistor Counts 1971-2011 & Moore's Law

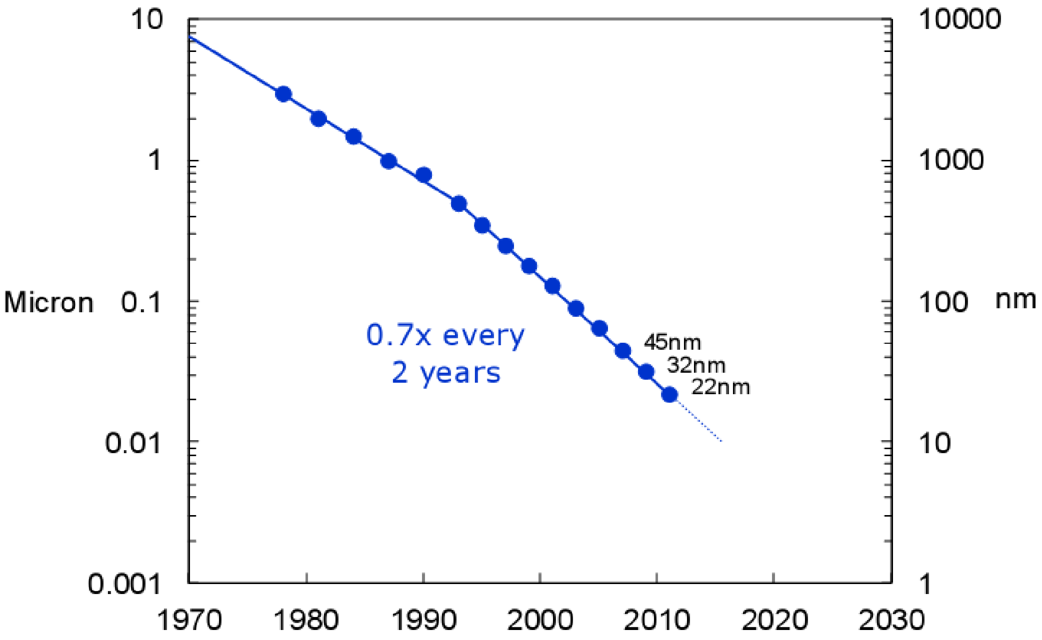


Fig. 1.6. Transistor dimensions scaling

This also means Intel can continue to lead in powering products, from the world's fastest supercomputers to very small mobile handhelds. Transistor size and structure are at the very center of delivering the benefits of Moore's Law to the end user. The smaller and more power efficient the transistor, the better. Intel continues to predictably shrink its manufacturing technology in a series of "world firsts": 45 nm with high-k metal gate in 2007; 32 nm in 2009; and now 22 nm with the world's first 3-D transistor in a high volume logic process beginning in 2011. The new technology enables innovative microarchitectures, System on Chip (SoC) designs, and new products – from servers and PCs to smart phones, and innovative consumer products.

Moore's law is about cost reduction, and about extreme cost reduction. The price per transistor on a chip has dropped dramatically since 1968. Some people estimate that the price of a transistor is now about the same as that of one printed newspaper character. In 1978 a commercial flight between New York and Paris cost around $900 and took 7 hours. If the principles of Moore's law had been applied to the airline industry the way they have applied to the semiconductor industry since 1978 then that flight would now cost about a cent and take less than 1 s. It is this economic aspect of Moore's law that has made electronics so pervasive.

Moore's law characterized by extreme miniaturization and extreme cost reduction is not only valid for ICs; for backend technology, i.e. packaging and assembly similar trends have also been observed. Taking some feature sizes of packaging and assembly as examples, one can see that wire diameters for bonding can be smaller than 10 μm; the interconnect pitch of wafer level packaging can be smaller than 20 μm; the thickness of copper film/trace in PCB can be smaller than 5 μm; the microvia diameters can be smaller than 20 μm; and the wafer thickness can be thinner than 20 μm. Clearly, Moore's law has not only driven the extreme miniaturization of the IC technology, but also pushed the packaging, assembly, and system level miniaturization, going beyond the visualization with our bare eyes.

Currently almost 70% of the total semiconductor components market is directly impacted by advanced CMOS miniaturization achieved by following Moore's law [1]. This 70% comprises three component groups of similar size, namely micro-processors, mass memories, and digital logic. The analog/mixed-signal market largely relies on variants of CMOS technology that are less affected by the miniaturization race due to other constraints, such as the need to handle power and/or high voltage.

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