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FROM RESEARCH
TO INDUSTRY

→ From the electron to chip manufacturing

8 → Microelectronics



- A TECHNOLOGICAL REVOLUTION
- A BRIEF HISTORY
- HOW ARE INTEGRATED CIRCUITS MADE?
- NANOELECTRONICS

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Microelectronics

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Observation of a silicon wafer using an optical microscope.

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Microelectronics enables new applications on account of its miniaturization and high performance. For example in medicine with this DNA-chip (on the right)

“Can electronic chips, which are constantly becoming more powerful and cheaper, go on being miniaturized?”

introduction

Cell phones, digital cameras, MP3 players, PCs, games consoles, bank cards, cars: in just a few decades, integrated circuits or "chips" have taken over most of the things we use everyday. This takeover is unprecedented in the history of technology. It reflects the accelerated pace of innovation in the microelectronics industry, which has gone on producing ever smaller transistors, resulting in turn in more powerful and efficient integrated circuits.

In 1971, the Intel 4004 processor contained approximately 2,300 transistors. In 2006, the prospect emerged of chips with a billion transistors. This amazing yet compact intelligence is becoming cheaper and cheaper: in 1973, it cost the price of an apartment to manufacture a million transistors; today it costs the price of a post-it.

Yet the outlook for the microelectronics industry is far from clear. Transistors will soon become so small that they will be extremely difficult to manufacture and operate. For example, the thickness of some (oxide) insulators may be no greater than 1 nm, that is, 3 or 4 oxide atomic layers!

Industry, research laboratories and institutes are setting in place research programs backed by heavy investment. This is especially the case in the Grenoble region, a world-class center for microelectronics. It is home to the CEA’s LETI (Laboratory of Electronics and Information Technology) and ST Microelectronics manufacturing in Crolles site combine forces. Finally, 4,000 people have been working in Grenoble since 1976 at Minatec, the leading European innovation cluster for micro and nanotechnologies.

40 YEARS OF CONTINUOUS PROGRESS AND NEW PRODUCTS AND SERVICES LIE BEHIND THE AGE OF MINIATURIZATION.

A technological revolution

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> **"On a 45 nm printed circuit the etchings are a thousand times thinner than a hair."**

MAKING MICROELECTRONICS MORE WIDELY ACCESSIBLE

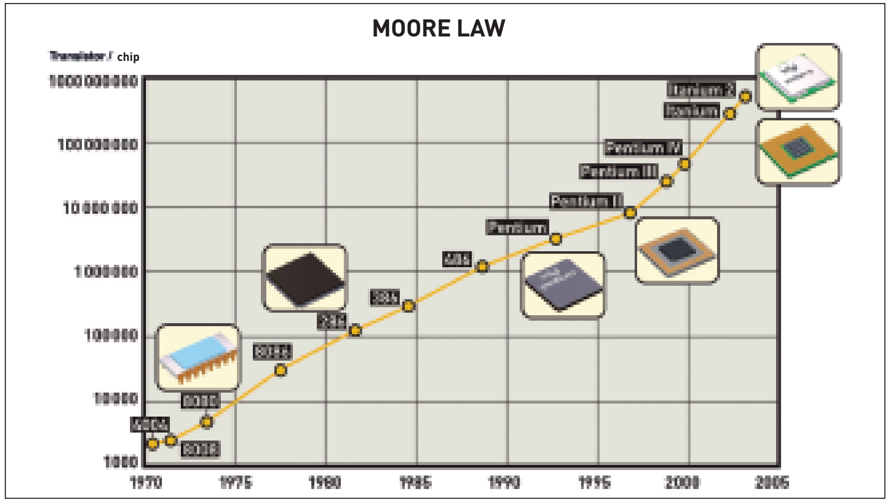
Microelectronics is not an established and stabilized business. The number of transistors per unit area quadruples every three years and the cost of the circuits halves every 18 months, particularly through mass production of hundreds of chips on each silicon wafer.

This growth curve in performance was described in 1965 by Gordon Moore, cofounder of Intel Corporation. It has proven so accurate that it is now known as "Moore's law" by all the manufacturers in the sector, who rely upon it to plan their investments and research programs years in advance.

In order to maintain this pace of development, we must constantly call into question: the materials used for circuits, electrical connections and insulators; circuit architectures, which represent a decisive factor in the final performance; production equipment, some of it costing several million euros; the size of the silicon wafers on which circuits are produced (200 mm and 300 mm), along with all the methods used in their manufacture.

To attain this level of performance, the most significant factor is how thin the etchings are. Initially this expressed in microns (millionths of a meter): 0.25 micron, then 0.18 micron,

etchings: This technic define the width of the patterns molded on the silicon.



"The power of current supercomputers can reach 1,000 billion operations per second... thanks to advances in microelectronics."

and then 0.13 micron. Since the turn of the century, the most commonly used unit is now the nanometer (a billionth of a meter). A production facility like Crolles produces 45 nm circuits or etchings a thousand times finer than the thickness of a hair.
These technological achievements have led to a fall in costs, an increased level of performance and more widespread use of microelectronics, with two consequences: constantly increasing computer power and new products and services for the general public.

MORE COMPLEX COMPUTATION FOR DESIGN, SIMULATION AND MODELING...

Post-war scientists carried out their calculations on computers that occupied entire rooms, and whose performance was no greater than that of a modern calculator. Early twenty-first century scientists have supercomputers whose performance reaches the teraflop.

teraflop: 1,000 billion operations per second.

Advances in integrated circuits are the cause of this giant leap, which has opened new possibilities:
- The design of complex systems or products. This can be done entirely on computer. Depending on the expected conditions of use, the computer calculates the behavior of the materials, the dimensions of the components, and their spatial layout, and then draws the plans.
- Phenomenological modeling. The behavior of an airliner in turbulence or five-day changes in the weather depend on a whole host of parameters. They can be modeled, that is represented by a series of complex operations whose result is very close to the actual phenomenon.
- Computer simulation. This time the process involves "manipulating" the models. For example, by providing the weight of the aircraft and its speed, plus the strength and direction of the turbulence, the computer can then predict its

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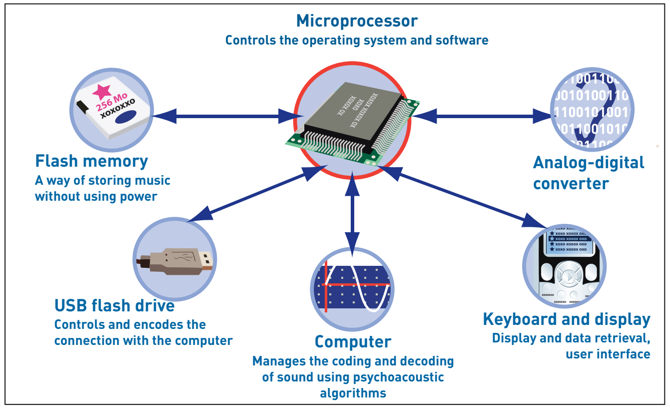
ENIAC, the first computer.

© C. Dupont / CEA

Tera, the new supercomputer.

INTERNAL DESIGN OF AN MP3 PLAYER



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in-flight behavior. In design terms, computer simulation allows an engine to be tested, for example, before producing a prototype, to see how it will be affected by heating, road vibrations or shocks.

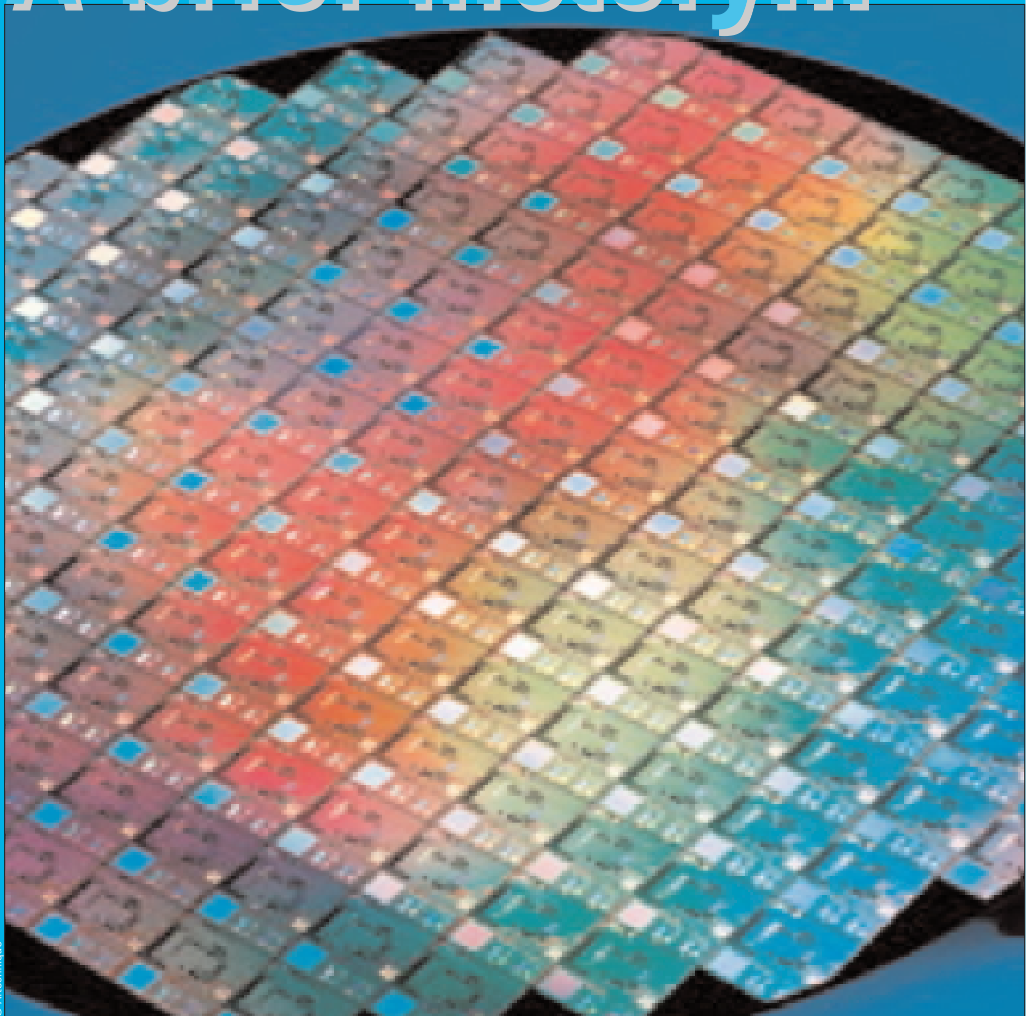
INNOVATIVE PRODUCTS AND SERVICES

The computing power of integrated circuits can offer the general public high-performance, user-friendly equipment, with a whole range of features: cell phones, DVD players, digital televisions, MP3 players, digital cameras, bank cards, and so on. The chips power both the computing functions and the interfaces (such as the keyboard, display, and USB) that make them intuitive and easy to use.
Moreover, the size and price of the products are steadily decreasing. The consumer is the winner on all fronts. The cell phone provides a perfect illustration of this phenomenon. The first devices, which were very bulky, could "only" be used to make telephone calls. The latest models are ultra-lightweight and feature games, HD cameras, and Internet connection for the same price or less.
Finally, it should be borne in mind that most such equipment includes not one but several integrated circuits (microprocessors and memory) that have been carefully designed to work together and enhance the overall performance of the device.

"The most successful consumer products have more features, are more compact, and cheaper."

IN A CENTURY, MINIATURIZATION HAS ENABLED THE TRANSITION FROM THE VACUUM TUBE TO THE ONE-MICROMETER-SQUARE TRANSISTOR.

A brief history...



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1904

John Alexander Fleming, an English engineer, invents the diode. This was the first electronic device and was used in radio receivers. In 1907, Lee de Forest, an American researcher, develops the principle further by inventing the triode.

1948

John Bardeen, Walter Brattain and William Shockley, three physicists at the Bell Laboratories (USA), produce the first transistor. Reliability, smaller size, reduced power consumption: the route to miniaturization opens up. This major discovery would win them the Nobel Prize for Physics in 1956.

1954

Texas Instruments manufacture the first silicon transistor. They were the size of dice, but within a decade would be as small as a grain of salt. However, the vast number of connecting threads holds back the development of complex circuits.

a few key dates the history of microelectronics a few key

THE DIODE, THE KEY ELECTRONIC DEVICE

The history of electronics began in 1904 with the invention of the diode, used in radio sets. A diode is a vacuum device comprising a filament that emits electrons and a plate that collects electrons when it is positively charged (electrons have a negative charge). The positive or negative voltage of the plate is changed in order to make or break the flow of current.
In 1907 the triode appeared, in which a grid is added between the filament and the plate. This grid acts as a modulator of the electrons: depending on its polarization, it either blocks them or makes them flow faster (current amplification).
During the 1940s, triodes and other types of valves were used in the first electronic computers capable of performing calculations faster than a human being. The numbers and tasks were coded in binary, using 0 or 1. For instance, 1 corresponds to the flow of electrical current, 0 to it being stopped. However, to carry out complex calculations such as those required by physicists, the number of vacuum tubes needs to be multiplied, and they are bulky, produce lots of heat and "fail" easily. This lack of reliability held back the development of computing.

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Vacuum diodes and transistors from 1965 (above).

WHERE DOES THE WORD "BUG" COME FROM?

The English word bug usually denotes an insect or "creepy crawly". So then how is this connected with the bugs in software? It is quite simple. With ENIAC, the world's first computer, developed at the University of Pennsylvania in 1946, a major cause of failure was small butterflies landing on electrical connections.

These were all the more numerous because ENIAC was a 30-ton monster, occupying 72 square m and using more than 17,000 vacuum tubes.

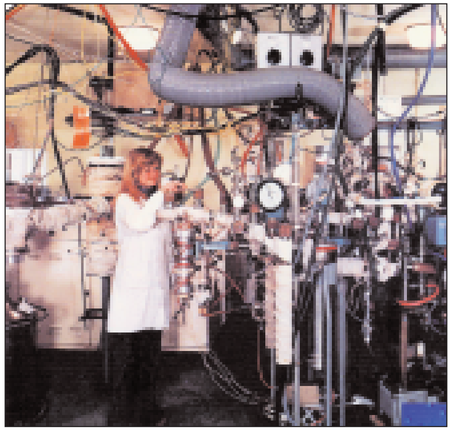
This was how bugs came to be part of the world of computing...

“With the transistor, electrons move through solid material and no longer through a vacuum.”

FROM TRANSISTOR TO INTEGRATED CIRCUIT

In 1948, John Bardeen, Walter Brattain and William Shockley, three American physicists, invented the bipolar transistor and in doing so opened up the age of microelectronics.
The bipolar transistor consists of an electron emitter, a collector and a modulation device known as a base. The movement of electrons no longer took place in a vacuum but in a solid material, semi-conductors by which the ability to drive the flow of electrons is controlled. Reliability improved considerably.
In addition, transistors were more compact than vacuum tubes.

> **semi-conductors:** This is made either of germanium or of doped monocrystalline silicon, for example.



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Technology research laboratory in the 1980s.

Within a few years, they went from being the size of dice to the size of a grain of salt!
The transistor was used in new radio sets - to which it gave its name - and in computers.
Yet another obstacle quickly became apparent: the more transistors there were, the more welded copper threads were needed to connect them, leading to a high risk of failure.
In 1959, the invention of the integrated circuit solved this problem. The transistors were manufactured directly on the surface of the silicon, and their connections were made by depositing metal layers on this surface.
There were no further obstacles to the manufacture of increasingly complex devices, combining transistors, diodes, resistors and capacitors. The very first integrated circuit consisted of six transistors. These devices would continue to be miniaturized and become more dense.

MODERN INTEGRATED CIRCUITS

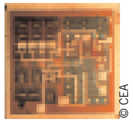
In 2005, a microprocessor (the most complex integrated circuit) is a piece of silicon plate about 2.5 square cm. It can contain several hundred million components. It is known as a “chip" and enclosed in a protective case with "legs" which provide connections with other components of the device in which it operates.
Most transistors are MOS (standing for Metal Oxide Semiconductor), a technology developed in the 1970s. This enables the manufacture of transistors that consume less and allows the integration of resistors, another

a few key dates in the history of microelectronics a few key dates

1959
Jack Kilby and Robert Noyce, two American researchers, produce the first integrated circuit, consisting of six transistors. Most importantly, they solve the problem of welding connections, which are produced by deposition of metal layers on the silicon.

1960
In the United States, the launch of the Apollo program, with $25 billion funding, gives a tremendous boost to research on computers and integrated circuits.

1964
First integrated circuit produced by CEA/LETI



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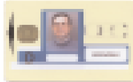
1974
The French engineer Roland Moréno invents the smart card.



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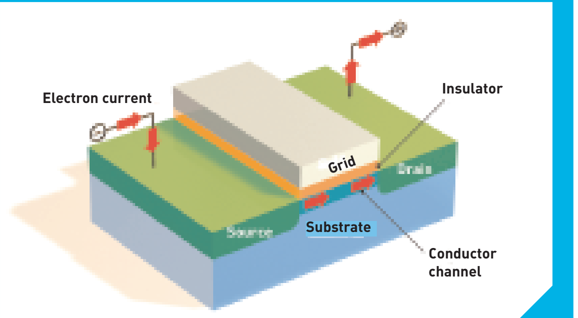
HOW DOES A MOS TRANSISTOR WORK?

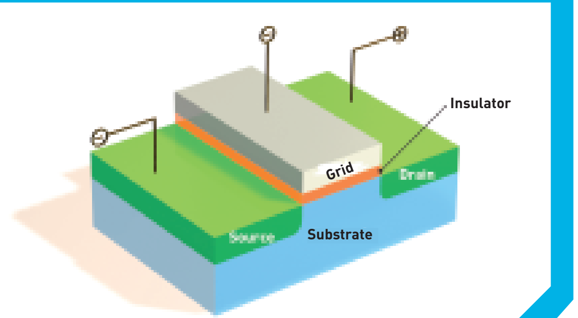
A MOS transistor consists of a source and a drain between which electrons can flow via a conductor channel.
This channel acts as a switch, depending on the electric charge of the grid.

Depending on the polarity of the grid, the conductor channel is either open or closed.

The performance of the transistor depends mainly on the size of the grid. The smaller this is, the shorter the distance the electrons have to travel in the channel and the quicker the system.



Conductor transistor (switch closed)



Blocked transistor (switch open)

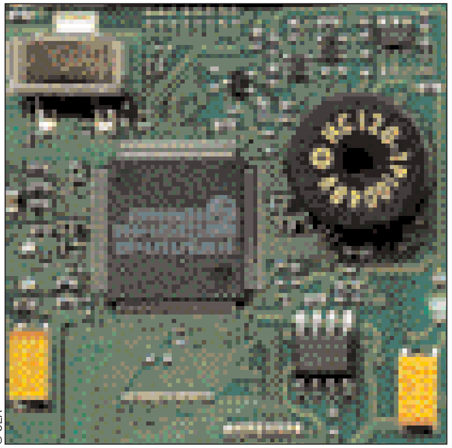
1991
Michel Bruel, a researcher at CEA/LETI, invents the Improve process for Silicon On Insulator (SOI) manufacture, increasing productivity tenfold. SOI will become the key material for producing fast, energy-efficient circuits.

1996
The Intel Pentium Pro processor uses 5.5 million transistors. This would be followed in 1999 by the Intel Pentium III (9.5 million) and in 2002 by the Intel Pentium IV (55 million). This compares with 2,300 transistors in the first Intel microprocessor, the 4004, released in 1971.

2003
First industrial production of chips on silicon wafers 300 mm in diameter.

a few key dates in the history of microelectronics. a few key date

important component of integrated circuits. The size of integrated circuits regularly increases. The size of the silicon plates on which the circuits are manufactured also increases to maintain the same number of chips on each plate. Over the past twenty years, the microelectronics industry has used a succession of silicon ingots: 100 mm in diameter, then 200 mm, and then 300 mm.
The silicon is not used in pure form: it is "doped" by adding very small quantities of foreign ions (arsenic, boron, phosphorus) that guide and facilitate the flow of the current.
The circuit can be etched on solid silicon or a thin layer of a few hundred nanometers deposited on an insulator.
Silicon On Insulator or «SOI» , which can make faster and more energy-efficient circuits, is increasingly used. The best manufacturing process was invented in 1991 by a CEA researcher.



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"A modern microprocessor consists of several billion components on a 2.5 cm square."

To produce the "infinitely small" gigantic factories are needed.

How are integrated circuits made?

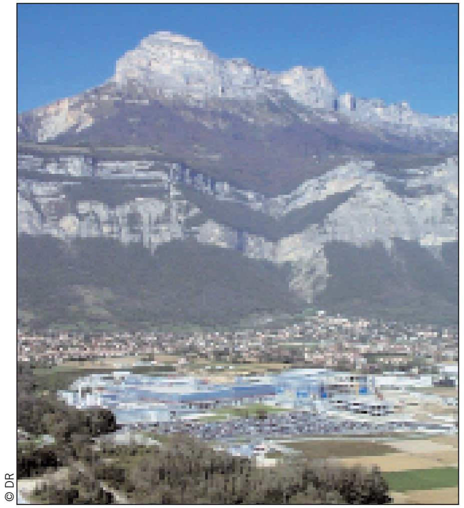
© P. Stroppa / CEA

INCREASINGLY EXPENSIVE PLANT

Manufacturing an integrated circuit involves producing a collection of millions of interconnected components on a surface a few centimeters square and a few microns thick, and doing this for hundreds of identical copies simultaneously.

The more integrated circuits are miniaturized, the more expensive the factories that manufacture them become. A “fab” (a production unit) costs roughly the same price as 300 Airbus 320s! There are several reasons for this:

- The smaller the circuits become, the cleaner the working environment needs to be to avoid critically contaminating them. The requirements for clean rooms are increasingly stringent.
- The smaller they become, the more the production machines are accurate, reliable, and difficult to develop and maintain. In addition, they are only manufactured in small series.
- The smaller they become, the greater the need for special materials, technically complex solutions and additional manufacturing steps. Today there are around 200 of these per circuit.



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Production facility of ST Microelectronics, at Crolles (Isère).

Despite all these efforts, the number of functional chips on a production line does not exceed 20% at the launch of a new production facility. The efforts of the production team will quickly increase this figure to 80% or even 90%.

Number of functional chips produced as a proportion of the number of chips manufactured.

“The price of a production unit is equivalent to the cost of 300 Airbus A320s.”

“The air in clean rooms contains between 100,000 and 1,000,000 times less dust than the air outside.”

THE CLEAN ROOM, AN ULTRA PURE ENVIRONMENT

On the scale of an integrated circuit, a miniscule dust particle appears like a giant boulder blocking the channels that have been dug out for the electron flow. This is why production takes place in what is known as a clean room.

A place where the humidity, temperature, water and chemicals produced are strictly controlled.

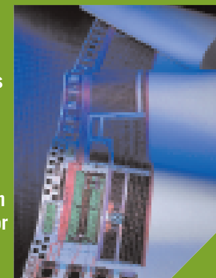
The air is filtered and changed ten times a minute. It contains 100,000 to 1,000,000 times less dust than the air outside. Workers always wear overalls that cover them from head to toe and retain the organic material and dust particles that they produce naturally.

In addition, many cleaning processes are carried out on the wafers between the stages of manufacture. In total they account for almost a third of the total processing time.

CAD: TOWNS SCALED DOWN TO CENTIMETER SIZE

It is impossible to design a circuit of several million elements without using a computer:

Every chip designer uses CAD (Computer-aided design) to determine the main functions, select the modules in the stored libraries, arrange these modules in relation to each other, simulate the operation, etc. The exercise is long, difficult and incredibly detailed.



If you imagine that a microprocessor with 100 million transistors had a side measuring 6 square km (the surface area of a town of 100,000 inhabitants), then each grid transistor insulator would be only one millimeter thick!

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A clean room at LETI, to CEA Grenoble.

© DR

300 mm silicon bar.

MASS PRODUCTION, A VITAL ASSET

The base material for the integrated circuit is silicon, the most widespread chemical element on Earth. It is extracted from sand by reduction, crystallized in the form of bars 20 or 30 cm in diameter, then cut into wafers less than one millimeter thick, which are polished to obtain smooth surfaces of around 0.5 nanometers.

Hundreds of chips are produced simultaneously on this wafer through the repetition or combination of basic operations, heat treatment, deposition, photolithography, etching, cleaning, polishing and doping.

This mass production, which brings down unit costs, is one of the key assets of the microelectronics industry. It explains why microsystems manufacturers seek to produce their products with the selfsame technologies. Yet it also imposes restrictions on production: a handling error, a few seconds more or less and several hundred circuits will end in the garbage can...

"Mass production of hundreds of copies reduces the unit cost per chip."

THE BASIC OPERATIONS

1 HEAT TREATMENT

Carried out in ovens at temperatures of 400 to 1,200°C, it can be used to make layers of oxides, dielectrics to rearrange crystal lattices or to conduct certain doping operations.

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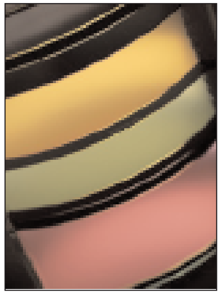
2 DEPOSITIONS

These put conductive or insulating layers on the surface of silicon: oxides, nitrides, silicides, tungsten, aluminum, copper, etc. They are produced by various techniques using gases or liquids: chemical vapor deposition (CVD), physical vapor deposition (PVD), pulverization, epitaxy, electrodeposition, etc.



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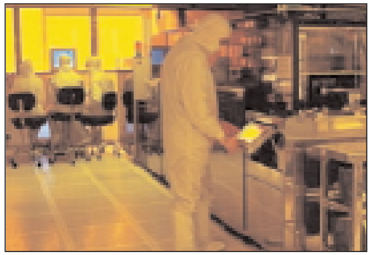
3 PHOTOLITHOGRAPHY

This is a key step and involves reproducing the circuit design to be created in a photosensitive resist. The resist is deposited on the substrate. The light from a very low wavelength light source (UV or lower) projects the image via a mask. The higher the optical resolution, the more the miniaturization of the circuits can be improved.



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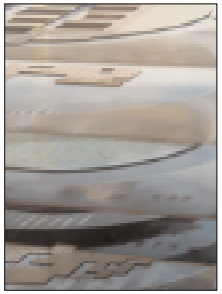
4 ETCHING

In contrast to deposition, etching removes material from the wafer, with the aim of producing a pattern. There are two main methods: "wet" etching, which uses reactive liquids, and dry (or plasma) etching, which uses reactive gases.



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5 CHEMICAL MECHANICAL POLISHING (CMP)

This basic step combines a mechanical rotational motion and a chemical effect in order to planarize the surface of the wafer and to improve its quality. To do so, a part of material is removed. This technique, used several times during the integration, improves also the performance of the photolithography witch is realized on a flat surface.

© DR

6 DOPING

To introduce atoms that will change its conductivity into the core of the silicon, are realized by implantation or heated in ovens to between 800 and 1,100°C, in the presence of dopant gas, or bombarded with an accelerated ion beam through a mask.

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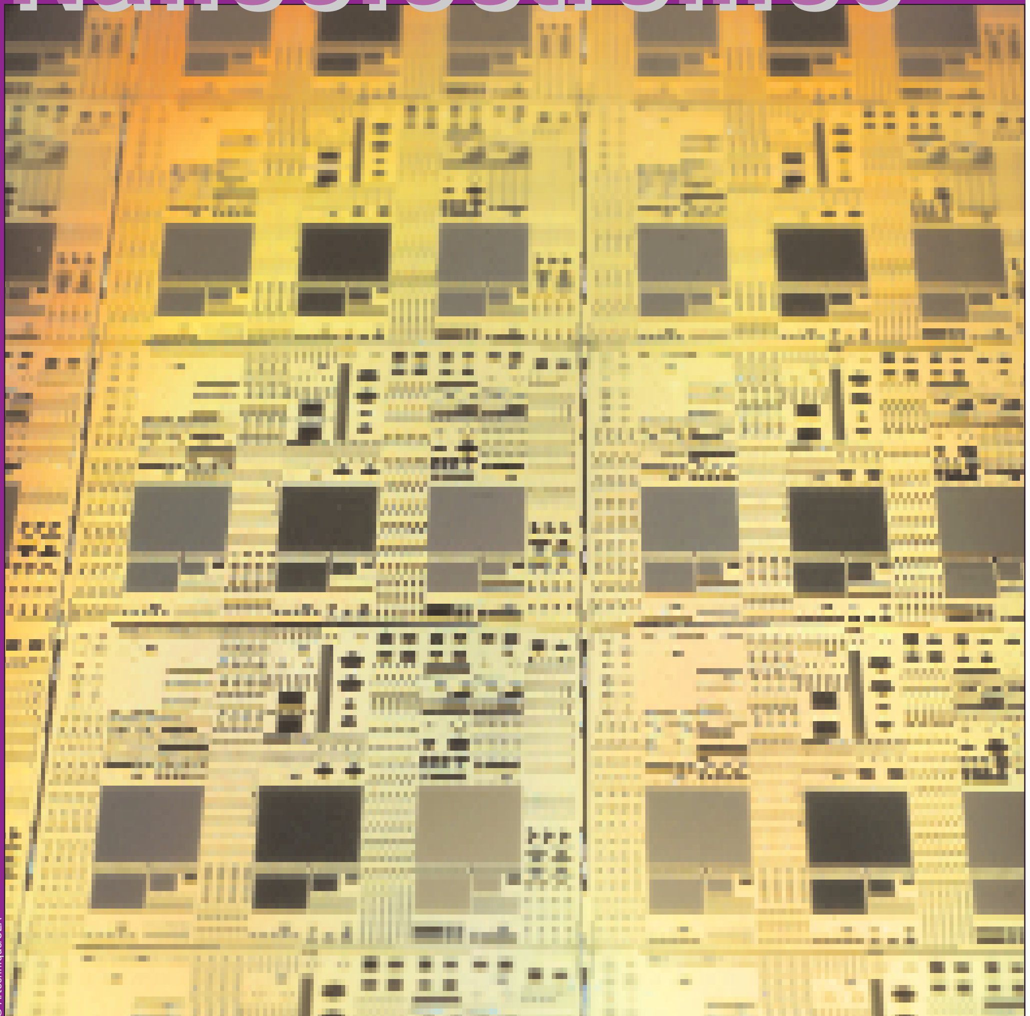
AT THE CROSSROADS OF PHYSICS AND CHEMISTRY, A NEW CHALLENGE FOR MICROELECTRONICS IS EMERGING, BRINGING WITH IT DISCOVERIES, APPLICATIONS AND JOBS.

Nanoelectronics



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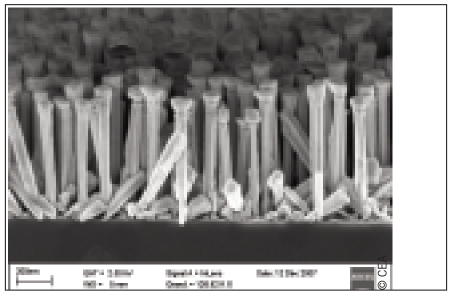
"It is now possible to assemble the material atom by atom, to build transistors with a completely new design."

"TOP DOWN" AND "BOTTOM UP"

The advent of nanotechnology brings with it technical challenges so ambitious that they could act as a brick wall against the powerful stream of innovation that runs through the industry. How can we etch lines that are only a few nanometers thick? How can we effectively insulate electrical tracks with materials no more than a few atomic layers thick? How can we make transistors through which only a handful of electrons can pass?

Two approaches are being pursued in parallel to overcome these obstacles:

- The **top down** approach: this involves pushing to the limit the extreme miniaturization of the MOS transistor, continuing the work of the past 40 years;
- The **bottom up** approach: this instead involves assembling the material atom by atom, to build molecules that are then joined in transistors with a completely new design. This approach makes use of basic knowledge of physics and chemistry, disciplines to which microelectronics should open up.



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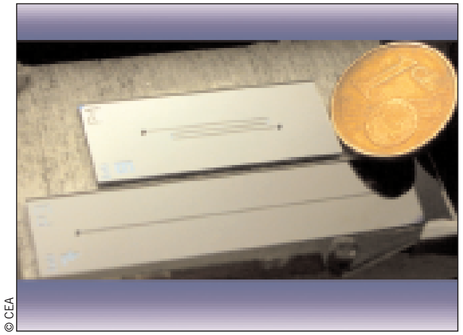
Nanofils.

THE WAY FORWARD FOR NANOTECHNOLOGIES

In another major development, microelectronics will interfere more and more with the world of micro and nanosystems: accelerometers for airbags, clothing that can communicate, camera capsules to introduce a micro-camera into the body, biochips for biological analysis, laboratory chip analysis, etc.



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Biochip Lab[PM].

These devices combine sensors and chips, which are essential for processing the data gathered. Their production will necessarily call for nanoelectronic technologies to meet miniaturization and cost objectives. We are at another cultural and disciplinary crossroads, namely between electronics and micro and nano-level systems.