Glossary

MEMS: microelectromechanical system.

mesoscopic: situated at an intermediate scale between the microscopic and macroscopic scales. A **mesostructure** is a structure with this scale.

metabolome: all the organic compounds (metabolites) present in a cell that have been either produced by its **enzymes** (coded by its **genome**), or taken up from its environment.

micelle: a spherical organization of **molecules** each comprising a **hydrophilic** part and a **hydrophobic** part. In an aqueous medium, the hydrophilic parts point out into the water and the hydrophobic parts are turned into the centre of the sphere.

micrometre (or **micron**)**:** 1 **µm** = 10^{-6} metre.

model: a simplified representation of a system or a process designed to simulate it. A **numerical model** is a model translated into a computer program (often called **code**).

mole: (symbol: **mol**) the quantity of matter in a system containing as many **atoms** or **molecules** as there are atoms in 0.012 kg of carbon-12, namely $6.03 \cdot 10^{23}$ (Avogadro's number).

molecular dynamics: the study of the movement of **atoms** within a **molecule**, in a solid, liquid or gas, by applying the laws of classical Newtonian mechanics to simulate the atomic movements in time. These movements correspond to vibrations around a minimum, or to the transition from one energy minimum to another.

molecule: a group of **atoms** linked together by chemical bonds.

Monte-Carlo method: a statistical method for approximating the value of an integral using a set of points distributed randomly according to a certain probability. It consists in repeating the assignment of a numerical value depending on the time course of a process in which chance is involved, and then calculating an average and its statistical dispersion (translating its accuracy) over all the values obtained. The method is useful for obtaining numerical solutions to problems that are too complicated to solve analytically.

MRAM: magnetic (dynamic) random access memory.

nanometre: 1 **nm** = 10^{-9} metre.

nanoparticle/nanostructure: a particle or structure of **nanometric** size.

nanostructuring: the formation of structural motifs at the **nanometre** scale.

nanowire: a one-dimensional structure made of a **semiconductor** material with a diametre of the order of 1 to 10 **nm** and a length ranging from a few **nanometres** to a few **micrometres**.

***n*-doping:** doping resulting in an excess of **electrons**.

NEMS: nanoelectromechanical system.

neutron: electrically neutral elementary particle of mass $1.675 \cdot 10^{-27}$ kg. The nuclei of **atoms** are made up of neutrons and **protons**.

NMR (nuclear magnetic resonance)**:** its principle is based on the properties that certain nuclei of **atoms** exhibit when they are placed in an intense magnetic field. They can interact with radio waves and emit signals (spectra or images) that help to identify the structure of the compounds present.

nucleation: the aggregation step in the correct assembly of growing objects. In a **polymer**, this process retards the assembly of the **monomers**.

nucleic acid: a **polymer** composed of a chain of **nucleotides**. There are two types of nucleic acid; **RNA** (ribonucleic acid), in particular **messenger RNA**, which specifies the **sequence** of **amino acids** in a **protein**, and **DNA** (deoxyribonucleic acid), which serves as a support for **genetic** information inside every living cell.

nucleotide: the structural unit of a **nucleic acid**, consisting of a nitrogen base, a five-carbon glucide and one or more phosphate groups.

numerical aperture (NA)**:** variable used to characterize luminosity and describe the depth of field and **resolution** of the optical system of an objective lens (especially in a microscope). It is calculated using the formula $n\sin\theta$, where 2θ corresponds to the angle (angular aperture) of entry of an object point in the optical axis at the entry point, and n is the refractive index of the object's support. The resolution is the ratio of the wavelength of the light to the numerical aperture.

optical index (refractive index)**:** a dimensionless quantity that describes the resistance of a material to light penetration. This index, which depends on the ratio of the speed of light in a vacuum to that in the medium being considered, is equal to the ratio of the sine of the incident angle to the sine of the refracted angle when light crosses the boundary between one medium and another.

optical pumping: procedure used in lasers to obtain a *population inversion*, which consists in supplying the energy necessary to obtain more excited **atoms** (at a higher energy level) than non-excited atoms (at a lower energy level), by exposing them to a powerful flash.

osmosis: transfer of a solvent from a dilute to a concentrated solution through a membrane. **Electro-osmosis**: osmosis under the influence of an electric field, from the positive to the negative pole.

oxidation: reaction in which an **atom** or **ion** loses **electrons**. The most frequent type is that in which a compound combines with one or more oxygen atoms.

***p/n* junction:** zone in which an electric field is created between an *n*-type **semiconductor** (with extra **electrons**) and a *p*-type **semiconductor** (with missing electrons), which become positively and negatively charged, respectively.

PCR (*polymerase chain reaction*)**:** ***in vitro*** technique for amplifying a fragment of **DNA** using the **enzyme** DNA polymerase.

***p*-doping:** doping resulting in a deficit of **electrons**.

peptide: polymer made up of a small number of **amino acids**.

pH: measure of the concentration of hydrogen **ions**. Values of pH below 7 are *acidic*, those above 7 are *alkaline*.

phonon: the specific mode of vibration of the **crystal** lattice of a solid.

phosphorescence: light emission due to the *slow* relaxation of **atoms** excited by light (visible or non-visible) the energy of which is "recovered" by **electrons** in certain substances. This process of (photo)**luminescence** differs from **fluorescence** by the long time lapse between absorption and re-emission.

photobleaching: overexposure to excitatory light, which can "extinguish" **fluorescence**.

photon: quantum of energy of electromagnetic radiation. Elementary particle with neither mass nor electrical charge associated with that radiation (visible light, **infrared**, **ultraviolet**, gamma or **X-rays** according to its energy).

Glossary

photonic bandgap: a concept introduced in the eighties at the same time as that of photonic **crystals** with the suggestion of inhibiting, by the creation of an artificial periodicity in **dielectric** materials, the propagation of **photons** in a similar way to that of electrons with energy situated in a **bandgap** in **semiconductors**.

photo-oxidation: oxidation of a **molecule** fuelled by the energy of a **photon**.

photovoltaic effect: effect whereby light is converted directly into electricity by the production and transport of electrical charges in a **semiconductor** material containing a part with an excess of **electrons** and another with a deficit of electrons.

piezoelectric effect: effect shown by certain materials whereby they change their electrical **polarization** when subjected to mechanical pressure. The opposite effect also exists: an electric field applied to a piezoelectric material causes it to change shape.

pixel: the smallest element of an image.

plasma: a medium made up of **atoms ionized** to varying degrees, free **electrons** and **photons**.

polar molecule: a **molecule** within which the charges are not distributed evenly. In a single **covalent bond** between two heteronuclear **atoms**, if the atoms have different electronegativities, the barycentres of the negative and positive charges do not coincide. The bond is **polar**.

polarization voltage: the voltage that has to be applied to a **transistor** to obtain a desired **drain** current.

polarized: having an electric field vector that describes an electromagnetic vibration in a defined plane. A **polarizer** is a device that causes this vibration to remain in that plane. An **analyzer** is used to measure the rotation in the plane of the polarized light when it travels through a sample.

polymerization: the stringing together of **molecules** of **monomers** by **covalent bonds** to form a **polymer**, a macromolecule of high molecular weight and repetitive structure. **Copolymerization** combines two or more different monomers.

porphyrin: an **aromatic** heterocyclic macrocycle made up of four **pyrrole** subunits linked together on opposite sides by four methine bridges (-CH=) to form a conjugated 20-membered ring structure. Porphyrins are basic constituents of haemoglobin and chlorophyll.

precipitation: formation of a solid insoluble substance (**precipitate**) by a chemical reaction between two or more compounds in solution.

probe: in a **DNA chip**, each **DNA** strand that a complementary strand can come and pair up with at a **hybridization** site.

protein: main macromolecular constituent of cells, resulting from the **DNA**-coded linking of **amino acids**. An amino acid (there are 20 naturally-occurring amino acids) is an organic **molecule** containing an **amine** (NH_2) group and a **carboxylic** (COOH) group, which allows the formation of a **peptide** bond (CO-NH) between different amino acids.

proteome: all the **proteins** expressed by a cell and made by "translation" of **messenger RNA**, itself transcribed from genes, the complete set of which forms the **genome** of a particular species. **Proteomics** is the science of the proteome.

proton: elementary particle carrying a positive electric charge equal, but of opposite sign, to that of the **electron**.

pyrrole: a five-membered **aromatic** ring, four elements of which are carbon **atoms** and the other a nitrogen atom. Its molecular formula is C_4NH_5.

quantum (*adj.*): concerning or derived from the theory developed from Planck's quantum principle, whereby energy is transferred in **discrete** amounts called **quanta**, and **Heisenberg's uncertainty principle** according to which it is not possible to measure accurately and at the same time both the position and the speed of a moving particle.

quantum box: a component of **nanometric** dimensions in which no **electron** has any degree of freedom, being constrained by a **semiconductor** with a larger **bandgap**.

quantum dot (QD)**: fluorescent semiconductor** nano**crystals** that act as high-intensity inorganic fluorophores They are much less sensitive to **photobleaching** than organic fluorophores, which are broken down in minutes when exposed to an excitation source and gradually lose their fluorescence.

quantum well: a component of **nanometric** dimensions in which each **electron** can move in only two spatial dimensions, being restricted by a **semiconductor** with a wider **bandgap**.

quantum: an indivisible unit.

radio-frequency component: a component that processes a signal in the radio-frequency spectrum.

redox (for reduction/oxidation) **potential:** potential describing the affinity of a **molecule** for **electrons**; **redox centre**: molecular group involved in electron transfers between molecules.

redox reaction: a reaction in which a **reducing agent** loses one or more **electrons** to an **oxidizing** agent. In the final equilibrium state the oxidizing agent, the reducing agent and their respective conjugates coexist.

reduction: a reaction in which an **atom** or an **ion** gains **electrons** from a **reducing agent**. The opposite of an **oxidation** reaction.

refraction: the change in direction that a beam undergoes when it crosses the boundary between two different media.

relaxation: reversion of a system in a high energy state *(excited state)* to a lower energy state.

resistivity: specific resistance of a material to the movement of **electrons**.

resolution: the smallest discernable value of a measurable quantity that can be obtained or retrieved. It measures the ability of an optical system to discern or reproduce the details of a scene or its image.

seed growth: mode of **crystal** growth in which a single near-perfect seed crystal of a substance is first made and then left to grow in a supersaturated solution of that substance.

segregation: the separation of homogeneous species.

semiconductor: material that possesses a **bandgap**, which is neither a pure insulator nor a pure conductor at finite temperatures, and whose electronic properties can be varied. Some of these **electrons** that are very weakly linked to their **atoms** can become **conduction** electrons. They can be ***n*-type** (charge carriers mostly electrons) or ***p*-type** (**charge carriers** mostly **holes**) according to the **dopants** used. Semiconductors belong to three families depending on the groups of the Periodic Table that the elements belong to: **II-VI**, **III-V** or **IV**.

sequence: the order in which the constitutive elements of biological **polymers** (**DNA**, **RNA**, **proteins**) are arranged.

shot noise or **Schottky noise:** quantum noise due the **discrete** properties of light, **photons** being emitted randomly, or attributable to the particle properties of an electric charge flow. (The value of the shot noise variation is calculated using the Schottky formula).

silicon: the most widespread **semiconductor** used to make **integrated circuits**.

SOC (*system-on-chip*)**:** concentration on a single chip of all the hardware and software of a dedicated data processing system.

soft chemistry: chemistry generally performed in solution at low temperature.

SOI (*silicon-on-insulator*)**:** a technology in which an ultrathin silicon film is transferred onto an insulating mechanical support (via the *Smart Cut*™ process patented by CEA-Leti). This technique can enhance microprocessor performance while reducing their energy consumption.

sol-gel: a chemical synthesis process using a solution containing reactive precursors such as alkoxides and metal salts. It comprises two steps: **hydrolysis** and condensation (formation of a **covalent** network). The **colloidal** suspension (*sol*) is made up of a solid phase of particle size distribution (**granulometry**) between 1 **nm** and 1 **µm** dispersed in a liquid. After condensation, the solution evolves into a system of greater molecular complexity that immobilizes the solvent (*gel*).

spectroscopy: the study of the structure of matter using the radiation that it emits, or the changes that this radiation can undergo when it is made to travel through other materials.

specular reflection: the component of optical reflection that is defined by incident and reflected angles, in contrast to diffuse reflection.

spin: angular moment (or intrinsic internal rotation moment) of a particle. It can be integral or half-integral.

spintronics (or spin electronics)**:** the science of **electron spin**.

stem cell: a cell that can go on dividing indefinitely to give daughter cells that can then differentiate to produce different tissues.

steric: concerning or derived from the space occupied by **atoms** and **molecules**.

stoichiometry: the study of the proportions in which reagents in a chemical reaction combine and the products are formed. A reaction is said to be **stoichiometric** when the quantities of the reagents are in the same **molar** proportions as those indicated in the reaction equation.

superconductor: a metal or alloy whose **resistivity** falls sharply to a near-null value at a critical temperature (**superconductivity**).

supramolecular: concerning the use of weak interactions between **molecules**.

surfactant: a substance in which each **molecule** is made up of a **hydrophilic** part and a **hydrophobic** part. It reduces the surface tension of a liquid in which it is dissolved, solubilizes substances that are not water-miscible by the formation of **micelles** and destroys biological membranes by solubilizing their constituents.

suspension: a system where one or more phases are dispersed in a liquid or gaseous dispersion medium.

synchrotron radiation: radiation characteristic of any charged particle that undergoes an acceleration. In the case of relativistic particles, the radiation possesses exceptional properties (continuous spectral domain from **infrared** to **X-ray**, low divergence, polarization, coherence, temporal structure) that can be used to probe the structure and electronic properties of matter.

template - templating: pattern used to create "prints", sometimes with a porogenic effect.

thermolysis: heat-induced decomposition.

threshold voltage: the value that characterizes a **transistor**. It corresponds to the **gate** voltage that causes it to switch from the blocked state to the conducting state.

transcriptome: the transcribed part of a cell **genome** in given conditions, expressed in the form of messenger **RNA**.

transfection: process whereby genetic material (*e.g.*, **DNA** or **siRNA**) is inserted into a cell.

triode: a **diode** to which is added a **gate** that controls electron flow. It can be used as an amplifier.

turbulence: mode of liquid flow in which a random movement is superimposed on a mean movement.

ultraviolet (UV) radiation: region of the electromagnetic spectrum characterized by a wavelength of 100 to 400 **nm** breaking down into several sub-regions: the **near ultraviolet** (250 to 400 nm), *far ultraviolet* (180 to 250 nm) and "vacuum" ultraviolet (100 to 180 nm). **Extreme ultraviolet** (**EUV**) corresponds to wavelengths between 100 and 10 nm.

vacancy: vacant space left in a **crystal** lattice by a displaced **atom**.

valency: the number of bonds that an **atom** can form.

Van der Waals forces: forces of various types, of low intensity and short range, between neutral **atoms** and **molecules** (cohesive energy of the order of 0.2 **eV**/atom). **Van der Waals bonding** involves forces of attraction between instantaneous dipoles (due to the movement of **electrons**). The energy of this bond is a hundred times weaker than that of a **covalent bond**.

vicinal surface: the surface obtained when a **crystal** is cut in a plane at a slight angle to a crystal plane of high atomic density. It appears as a periodic succession of *terraces* separated by *steps* of monoatomic height.

virus: an organism that can reproduce only inside cells, and contains only one **nucleic acid**.

visible radiation: the part of the electromagnetic radiation spectrum in the wavelength range 400 to 760-780 **nm**.

wafer: a very thin slice of usually **silicon** on which are etched a large number of electronic circuits, and which is divided up to make **integrated circuits**.

waveguide: a device designed to guide one or more electromagnetic waves between two points at close range with minimal energy loss by radiation.

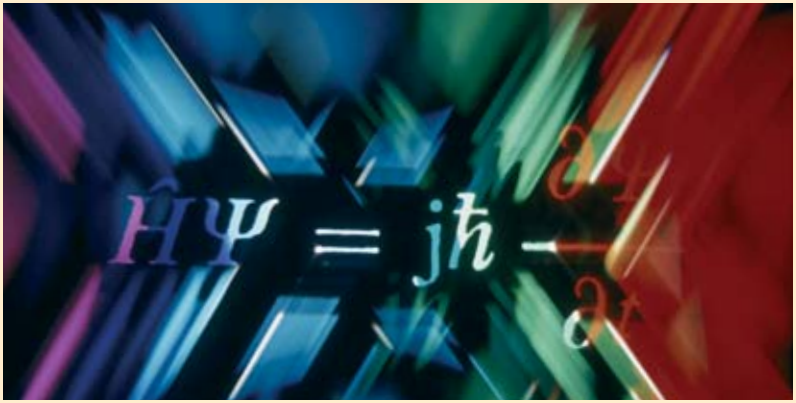
X-ray diffraction: method used to obtain information on the structure of matter, in particular **crystalline** matter. The wavelength of the beams is of the same order of magnitude as the internuclear distances.

X-rays: electromagnetic radiation of wavelength comparable to interatomic distances, covering the range 0.005 **nm** to 100 nm, and of energy between a few **keV** and several hundred keV.

B A guide to quantum physics

Quantum physics (historically known as quantum mechanics) covers a set of physical laws that apply at microscopic scale. While fundamentally different from the majority of laws that appear to apply at our own scale, the laws of quantum physics nevertheless underpin the general basis of physics at all scales. That said, on the macroscopic scale, quantum physics in action appears to behave particularly strangely, except for a certain number of phenomena that were already curious, such as superconductivity or superfluidity, which in fact can only explained by the laws of quantum physics. Furthermore, the transition from the validating the paradoxes of quantum physics to the laws of classical physics, which we find easier to comprehend, can be explained in a very general way, as will be mentioned later.

Quantum physics gets its name from the fundamental characteristics of quantum objects: characteristics such as the angular momentum (spin) of discrete or discontinuous particles called quanta, which can only take values multiplied by an elementary *quantum*. There is also a quantum of action (product of a unit of energy multiplied by time) called Planck's constant (symbolized as h) which has a value of 6.626×10^{-34} joule·second.



D. Sarraute/CEA

An "artist's impression" of the Schrödinger equation.

While classical physics separates *waves* from *particles*, quantum physics somehow covers both these concepts in a third group, which goes beyond the simple wave-particle duality that Louis de Broglie imagined. When we attempt to comprehend it, it sometimes seems closer to waves, and sometimes to particles. A quantum object cannot be separated from how it is observed, and has no fixed attributes. This applies equally to a particle - which in no way can be likened to a tiny little bead following some kind of trajectory - of light (photon) or matter (electron, proton, neutron, atom, etc.).

This is the underlying feature behind the Heisenberg uncertainty principle, which is another cornerstone of quantum physics. According to this principle (which is more *indeterminacy* than *uncertainty*), the position and the velocity of a particle cannot be measured *simultaneously* at a given point in time. Measurement remains possible, but can never be more accurate than *h*, Planck's constant. Given that these approximations have no intrinsically real value outside the observation process, this simultaneous determination of both position and velocity becomes simply impossible.

B (next)

At any moment in time, the quantum object presents the characteristic of *superposing* several states, in the same way that one wave can be the *sum* of several others. In quantum theory, the amplitude of a wave (like the peak, for example) is equal to a **probability amplitude** (or probability wave), a complex number-valued function associated with each of the possible sates of a system thus described as quantum. Mathematically speaking, a physical state in this kind of system is represented by a **state vector**, a function that can be added to others *via* superposition. In other words, the sum of two possible state vectors of a system is *also* a possible state vector of that system. Also, the product of two vector spaces is also the sum of the vector products, which indicates **entanglement**: as a state vector is generally spread through space, the notion of local objects no longer holds true. For a pair of entangled particles, *i.e.* particles created together or having already interacted, that is, described by the *product* and not the *sum* of the two individual state vectors, the fate of each particle is linked - entangled - with the other, regardless of the distance between the two. This characteristic, also called *quantum state entanglement*, has staggering consequences, even before considering the potential applications, such as quantum cryptography or - why not? - teleportation. From this point on, the ability to predict the behaviour of a quantum system is reduced to probabilistic or statistical predictability. It is as if the quantum object is some kind of "juxtaposition of possibilities". Until it has been measured, the measurable size that supposedly quantifies the physical property under study is not strictly defined. Yet as soon as this measurement process is launched, it destroys the **quantum superposition** through the "collapse of the wave-packet" described by Werner Heisenberg in 1927. All the properties of a quantum system can be deduced from the equation that Erwin Schrödinger put forward the previous year. Solving the **Schrödinger equation** made it possible to determine the energy of a system as well as the **wave function**, a notion that tends to be replaced by the probability amplitude.

According to another cornerstone principle of quantum physics, the **Pauli exclusion principle**, two identical half-spin ions (**fermions**, particularly electrons) cannot simultaneously share the same position, spin and velocity (within the limits imposed by the uncertainty principle), *i.e.* share the same *quantum state*. **Bosons** (especially photons) do not follow this principle, and can exist in the same quantum state.

The coexistence of **superposition states** is what lends **coherence** to a quantum system. This means that the theory of **quantum decoherence** is able to explain why macroscopic objects, atoms and other particles, present "classical" behaviour whereas microscopic objects show quantum behaviour. Far more influence is exerted by the "environment" (air, background radiation, etc.) than an advanced measurement device, as the environment radically removes all *superposition of states* at this scale. The larger the system considered, the more it is coupled to a large number of degrees of freedom in the environment, which means the less "chance" (to stick with a probabilistic logic) it has of maintaining any degree of quantum coherence.

TO FIND OUT MORE:

Étienne Klein, *Petit voyage dans le monde des quanta*, Champs, Flammarion, 2004.

D The transistor, fundamental component of integrated circuits

The first transistor was made in germanium by John Bardeen and Walter H. Brattain, in December 1947. The year after, along with William B. Shockley at Bell Laboratories, they developed the bipolar transistor and the associated theory. During the 1950s, transistors were made with silicon (Si), which to this day remains the most widely-used semiconductor due to the exceptional quality of the interface created by silicon and silicon oxide (SiO_2), which serves as an insulator. In 1958, Jack Kilby invented the integrated circuit by manufacturing 5 components on the same substrate. The 1970s saw the advent of the first microprocessor, produced by Intel and incorporating 2,250 transistors, and the first memory. The complexity of integrated circuits has grown exponentially (doubling every 2 to 3 years according to "Moore's law") as transistors continue to become increasingly miniaturized.

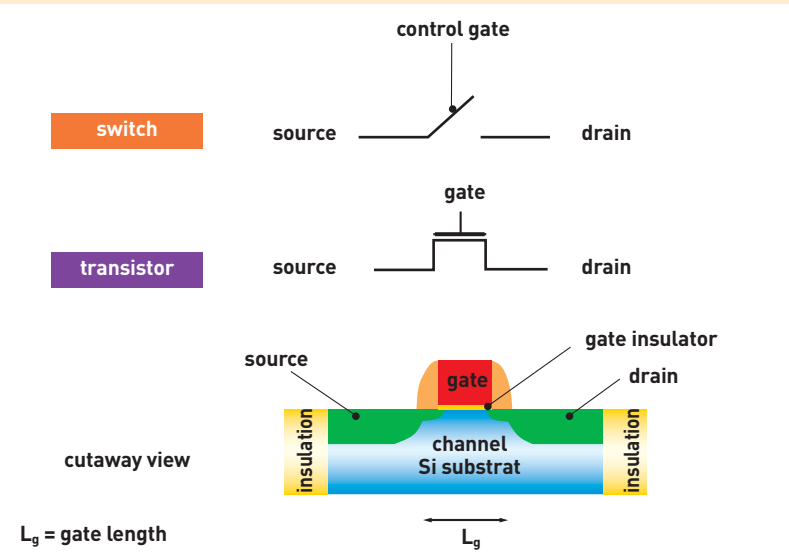


Figure.
A MOS transistor is a switching device for controlling the passage of an electric current from the source (S) to the drain (D) via a gate (G) that is electrically insulated from the conducting channel. The silicon substrate is marked B for Bulk.

The transistor, a name derived from *trans*fer and res*istor*, is a fundamental component of microelectronic integrated circuits, and is set to remain so with the necessary changes at the nanoelectronics scale: also well-suited to amplification, among other functions, it performs one essential basic function which is to open or close a current as required, like a switching device (Figure). Its basic working principle therefore applies directly to processing binary code (0, the current is blocked, 1 it goes through) in logic circuits (inverters, gates, adders, and memory cells).

The transistor, which is based on the transport of electrons in a solid and not in a vacuum, as in the electron tubes of the old triodes, comprises three electrodes (*anode, cathode* and *gate*), two of which serve as an electron *reservoir*: the source, which acts as the emitter filament of an electron tube, the drain, which acts as the collector plate, with the gate as "controller". These elements work differently in the two main types of transistor used today: *bipolar junction transistors*, which came first, and *field effect transistors* (FET).

Bipolar transistors use two types of charge carriers, electrons (negative charge) and holes (positive charge), and are comprised of identically doped (p or n) semiconductor substrate parts

D (next)

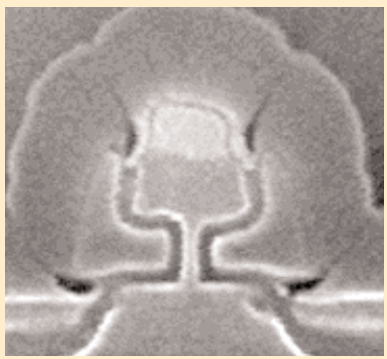
separated by a thin layer of inversely-doped semiconductor. By assembling two semiconductors of opposite types (a p-n junction), the current can be made to pass through in only one direction. Bipolar transistors, whether n-p-n type or p-n-p type, are all basically current amplifier controlled by a gate current[1]: thus, in an n-p-n transistor, the voltage applied to the p part controls the flow of current between the two n regions. Logic circuits that use bipolar transistors, which are called TTL (for transistor-transistor logic), consume more energy than field effect transistors which present a zero gate current in off-state and are voltage-controlled.

Field effect transistors, most commonly of **MOS** (metal oxide semiconductor) type, are used in the majority of today's **CMOS** (C for complementary) logic circuits[2]. Two n-type regions are created on a p-type silicon crystal by doping the surface. These two regions, also called drain and source, are thus separated by a very narrow p-type space called the **channel**. The effect of a positive current on the control electrode, naturally called the **gate**, positioned over the semiconductor forces the holes to the surface, where they attract the few mobile electrons of the semiconductor. This forms a conducting channel between source and drain (Figure). When a negative voltage is applied to the gate, which is electrically insulated by an oxide layer, the electrons are forced out of the channel. As the positive voltage increases, the channel resistance decreases, letting progressively more current through.

In an integrated circuit, transistors together with the other components (**diodes**, condensers, resistances) are initially incorporated into a "chip" with more or less complex functions. The circuit is built by "sandwiching" layer upon layer of conducting materials and insulators formed by **lithography** (Box D, ***Lithography, the key to miniaturization***). By far the most classic application of this is the microprocessor at the heart of our computers, which contains several hundred million transistors (whose size has been reduced 10,000-fold since the 1960s), soon a billion. This has led to industrial manufacturers splitting the core of the processors into several subunits working in parallel!

Lucent Technologies Inc./Bell Labs

The very first transistor.



STMicroelectronics

8 nanometre transistor developed by the Crolles2 Alliance bringing together STMicroelectronics, Philips and Freescale Semiconductor.

(1) This category includes **Schottky transistors** or **Schottky barrier transistors** which are field effect transistors with a metal/semiconductor control gate that, while more complex, gives improved charge-carrier mobility and response times.

(2) Giving **MOSFET** transistor (for Metal Oxide Semiconductor Field Effect Transistor).