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New concepts for nanophotonics and nano-electronics

From transistor to nanotube

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Abstract

We present here the main steps in the evolution of the transistor, since the tremendous invention of such a device and the introduction of the integrated circuit. We will then recall the main steps of Moore's law development. Nanotechnology began at the very beginning of the 21st century. Two aspects are presented in this article: the first, called 'More Moore', consists in continuing the laws of scale up to the physical limits; the second aspect, called 'beyond CMOS' explores new concepts such as spintronics, moletronics, nanotronics and other types of molecular electronics. ***To cite this article: J.-C. Boudenot, C. R. Physique 9 (2008).***

Résumé

Du transistor aux nanotubes. Nous présentons ici les principales étapes de l'évolution des transistors, depuis l'invention prodigieuse d'un tel dispositif et l'introduction du circuit intégré. Nous rappellerons alors les principales étapes du développement de la loi de Moore jusqu'à la naissance de la nanotechnologie, au début du XXI^{e} siècle. Deux aspects sont présentés dans cet article : le premier, appelé « More Moore », consiste en continuant la réduction des dimensions des transistors à parvenir jusqu'aux limites physiques, le deuxième aspect, appelé « beyond CMOS » explore de nouveaux concepts tels que la spintronique, la « moletronique », la « nanotronique » et autre type d'électronique moléculaire. ***Pour citer cet article : J.-C. Boudenot, C. R. Physique 9 (2008).***

Keywords: Transistor; Nanoelectronics; Road map; Molecular electronics

Mots-clés : Transistor ; Nanoélectronique ; Feuille de route ; Électronique moléculaire

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1. First steps

The revolution of nanotechnology coincides with the beginning of the 21st century. Thus, it is a very recent science, but it is possible to find earlier traces in the past. In the case of nanotechnology it is necessary to go back to the 4th century, at the time of the Roman Empire! The glass of Lycurgus (preserved at British Museum) presents the remarkable property of being red if it is lit from inside and green if it is lit from outside. This remarkable property is due to the presence (quite involuntary!) of particles of nanometric size (∼40 nm), which gives a red colour to the light transmitted and a green colour to the reflected light. However, such an example remains quite rare.[1]

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[1] One has also found silver and gold nanoparticules in Etruscan art object's; in Arab potteries of the 9th century, as well as in the coloured vases of Murano since the 16th century.

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The history of the transistor is based on three points. The first is the desire of man to have a machine carry out tiresome calculations. In this field, the methods slowly improved: after the Chinese abacus, the first calculating machine appeared in the middle of the 17th century. Blaise Pascal developed, between 1642 and 1645, an arithmetic machine able to carry out the four operations. This machine, the 'Pascaline', initially intended to help his father with his office accounts, was then produced with fifty specimens between 1645 and 1652.[2] Thirty years later Leibniz developed a new calculating machine, in 1671, more powerful than that of Pascal: in addition to the four operations (adding, subtracting, multiplying and dividing) it even made it possible to extract square roots.

The second important point in the history of the transistor is the invention in 1879 of the bulb by Thomas Edison. Sometime later, in 1883, Edison discovered the effect named after him: when one inserts inside a bulb a metal plate having a positive potential, a current passes from the filament to this plate. This device anticipated the diode at a time when the concept of the electron had not yet emerged. The following stage was reached by John Ambrose Fleming. This physicist, after having done research in Cambridge with James Clerk Maxwell, joined in 1882, the English subsidiary of the Edison company, before working for the Marconi's *Wireless and Signal Company*. Fleming invented the 'valve' (diode) in 1904 and its rectifying effect was quickly used for wave detection. Two years later, Lee de Forest improved Fleming's valve while inserting between the cathode and the anode a grid allowing one to control the signal. This tube was made up of three electrodes: the so-called 'triode' had been first named 'Audion' by Lee de Forest. One could indeed, thanks to him, transmit an analogical audio signal, because the triode was able to amplify weak signals. Lee de Forest was able to transmit, as early as 1908, spoken and musical emissions. The wireless transmission (TSF: 'Télégraphie Sans Fil') which was limited at this time to Morse signals, found new horizons. The third point, the most important, which contributed to the invention of the transistor, is the discovery of semiconductors. It was in 1874, when he was only twenty-four years old, that Ferdinand Braun discovered the rectifying effect of the galena crystal (PbS).[3] The same effect had been discovered sometime earlier, before 1900, by Edouard Branly. He tried to interpret radio-conduction. To do this, he imagined a device (the 'disk-tripod') showing that it is not necessary that the particles of a conductor be in contact to allow the electrical current to pass. The Branly's 'disk-tripod' consisted of three fine conducting needles in contact with a metal disk; this device lets the current pass only in one direction, making possible the rectifying effect. From 1901, Branly started to replace its 'coherer' by the disk-tripod, while Braun started to use the galena crystal and took part, in 1906, the realization of the galena radio-set. For his part, Captain Ferrié,[4] developed in 1900 an 'electrolytic detector' which was very sensitive (7 µW). A circumstance, very different from the TSF, will appeared essential. In 1940, Russel Ohl, a researcher in Bell Labs, worked on the photovoltaic effect. He invented the PN junction and showed that it can deliver a tension of 0.5 V when exposed to light.

At the end of World War II, in 1946, the Americans built the first electronic computer: the ENIAC. This monster, which carried out 5000 operations per second, weighed 28 tons, used nearly 18 000 tubes and consumed 200 kW. It was then obvious that the development of electronic computation needed an alternative to the electron tube. After 1945, Bell Labs decided to launch a research programme on this topic; the group was lead by William Shockley. As early as 1947, James Bardeen and William Brattain succeeded in making an amplifier circuit by using a "point-contact **trans**fer res**istor**" (**transistor**) (see Fig. 1). Sometime later, William Shockley invented the junction transistor. Six months later, the patents were deposited, one on the point-contact transistor by Bardeen and Brattain (June 17, 1948) (see Fig. 2), the other one on the junction transistor by Shockley (June 26, 1948). It soon appeared evident that the later was simpler to realize. Germanium, initially used, was soon replaced by silicon (the first silicon crystal was manufactured in 1952), which made possible for Texas Instruments to develop the first commercial silicon transistor in 1954. Then MESA technology (Texas Instruments), which is at the origin of the integrated circuits, appeared in 1957. A year later Fairchild introduced Planar technology (see Fig. 3).

The following step was achieved on September 12, 1958. Jack Kilby (1923–2005), from Texas Instruments, carried out the very first integrated circuit. It was composed of only 5 components of 3 types: transistor, resistance and

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[2] The basic *Pascaline* makes addition and subtraction, but starting from these two elementary operations, one can carry out multiplication, divisions and even extraction of square root. There were machines operating in 'base ten' able to make 'abstract calculations'. Others comprised an unequal number of subdivisions and were intended for accountancy.

[3] While placing a metal point in contact with the crystal of galena one could rectify the AC current. Let us note that Faraday had, as early as 1833, noticed that the electric conductibility of silver sulfide increases with the temperature (whereas it decreases for metals).

[4] Let us note that it was Gustave Ferrié who proposed, in 1912, to found the French National Committee of Scientific Radioelectricity (CNFRS).

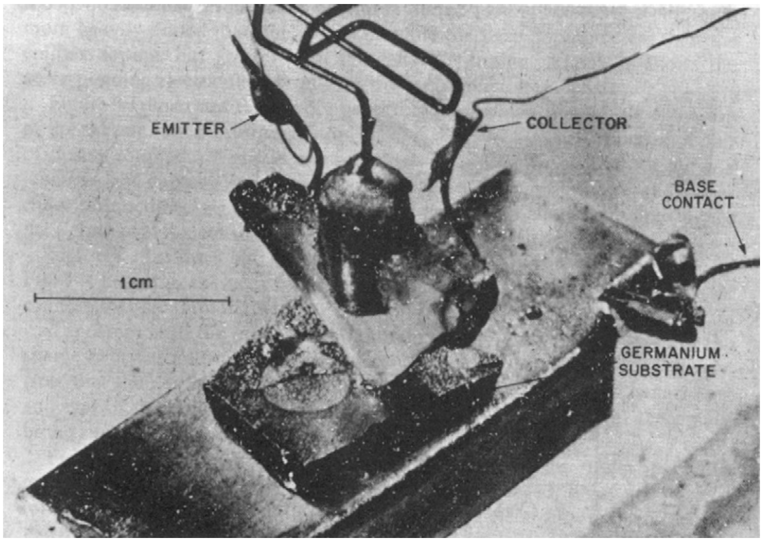
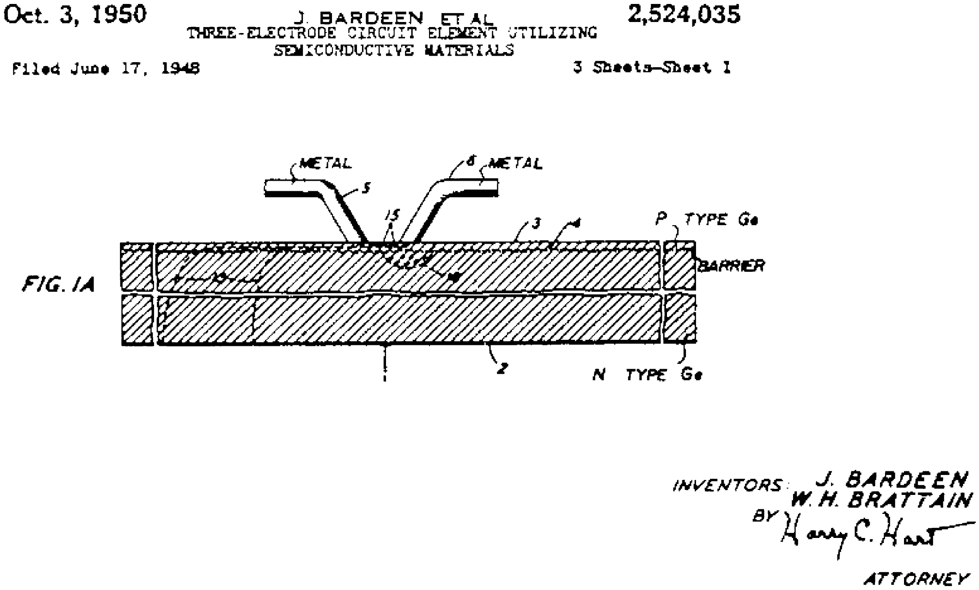


Fig. 1. The first transistor, 1947.



Oct. 3, 1950 J. BARDEEN ET AL 2,524,035
THREE-ELECTRODE CIRCUIT ELEMENT UTILIZING SEMICONDUCTIVE MATERIALS
Filed June 17, 1948 3 Sheets-Sheet 1

INVENTORS J. BARDEEN
W. H. BRATTAIN
BY Harry C. Hart
ATTORNEY

Fig. 2. Bardeen and Brattain patent for the transistor.

capacity. Forty two years later (in 2000) he was awarded the Nobel Prize for his discovery.[5] This realization would not have been the success which one knows without the invention of the field-effect transistor. The concept goes back to the years 1925 to 1928 and is due to J.E Lilienfeld. The idea was to make a solid state triode (the name grid came from this origin). The patent was deposited in 1928 and was granted in 1933, but there was no practical realization before 1959. John Attala, Dawon Kahng and E. Labate, thanks to the control of the interface states existing between the insulator of the grid and the semiconductor of the channel, succeeded in transforming the Lilienfeld concept into a

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[5] The Nobel citation specifies: “For his part in the invention of the integrated circuit”.

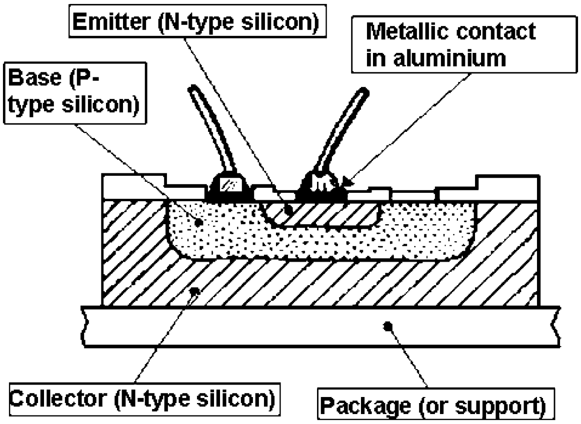
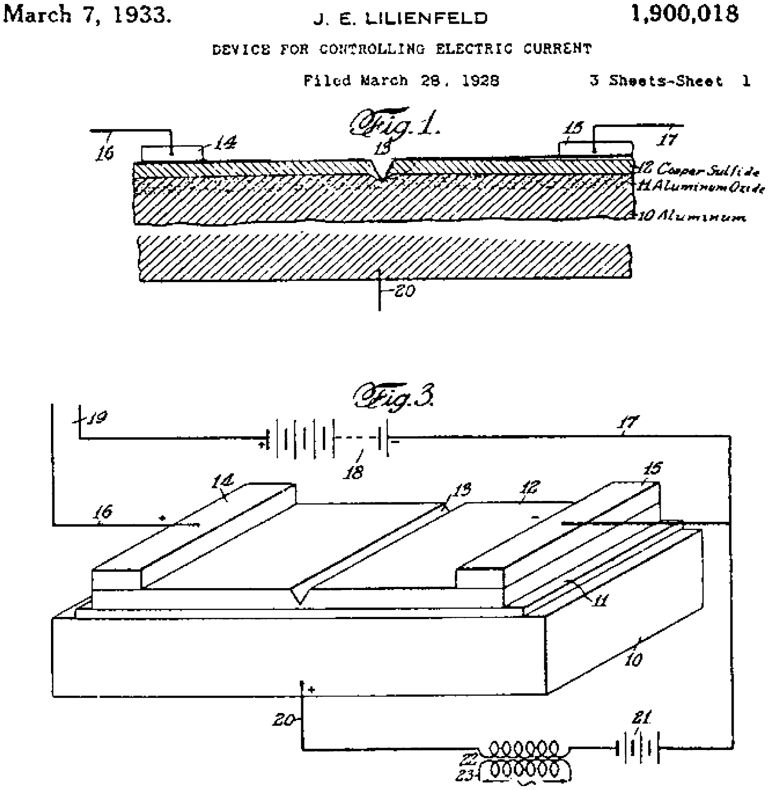


Fig. 3. Structure of a planar transistor.



March 7, 1933. J. E. LILIENFELD 1,900,018

DEVICE FOR CONTROLLING ELECTRIC CURRENT

Filed March 28, 1928 3 Sheets-Sheet 1

Fig. 4. Lilienfeld's patent of field-effect transistor, 1933.

functional device (Fig. 4). The first MOS (Metal Oxide Semiconductor) transistor was made in 1960,[6,7] while the first MOS integrated circuit was realized, simultaneously by Fairchild and Texas Instruments, in 1961. Let us note that the introduction of Transistor Transistor Logic (TTL) was made in 1962, the first pMOS circuit was produced by RCA in

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[6] Schottky and Mott give, as early as 1935, a complete model of the contacts metal-semiconductor. In 1939, Schottky and Spenke publish, in the Siemens' scientific review, a concept very close to transistor MOS. This concept will be exploited twenty years later by Hofstein and Heiman of RCA (MOST) and, independently, by Grosvalet of the CSF ('statistor').

[7] Less than fifty years later, the transistor is the manufactured object most widespread in the world: one manufactures 10^{19} per year, which corresponds to more than one billion transistors per capita of our planet, or hundred times the number of ants on Earth.

1963, a short time before the realization, by Frank Wanlass from Fairchild Semiconductor, of Complementary MOS (CMOS).[8]

2. Moore's law and integration

A turning point occurred in the middle of the 1960s. The impulse given by Jack Kilby with his first integrated circuit continued: one could integrate 8 ($= 2^3$) transistors on the same 'chip' in 1962; 16 ($= 2^4$) in 1963; 32 ($= 2^5$) in 1964; 64 ($= 2^6$) in 1965. At this point, Gordon Moore made the prediction that this tendency must continue and that one should reach an integration of $2^{16} = 65\,000$ transistors in 1975! "*Such a density of components*", explained Gordon Moore, "*can be obtained by the current optical techniques. Only an engineering effort is necessary*" [4]. More than forty years later this law still controls the evolution of micro, or rather, of nano electronics. In 1971, the first microprocessor appeared: the 4004 of INTEL. Its characteristics seem today to come from another age: 4-bit microprocessor having 2300 transistors, a 10 µm pMOS technology, with a frequency of 108 kHz, 2 kbits of ROM and 320 bit of RAM, finally the chip had a surface of 3.5 mm^2. In 1972, the first scientific pocket calculator (HP 35) appeared on the market: it included only 4000 transistors (10 µm technology!). The famous Motorola's 68 000 microprocessor appeared in 1979, owing its name to the fact that it had 68 000 transistors (3 µm technology). INTEL's response came in 1982, with the launch of the 80 286 microprocessor (surface of the chip = 68.7 mm^2), functioning at a frequency of 10 MHz and having two metal levels (technology 1.5 µm). Nearly twenty-years later (in 2000) the Pentium 4 microprocessor integrated 42 million transistors (technology 0.18 µm). Six levels of metal were necessary to contact these transistors and its frequency was 1.5 GHz, while the dimension of the chip reached 224 mm^2. The last microprocessor (launched in 2006) was the Itanium 2 – Montecito, which does not have less than 1.72 billion transistors [90 nm (0.09 µm) technology].

Thus, in a little more than forty years, the integration of electronics passed from the discrete transistor to nearly 2 billion transistors on the same chip. We use to define the border between micro and nano electronics by the passage under the bar of the 100 nm for the width of the grid of the transistor, so this threshold was crossed in 2003 (see Fig. 5). The width of the transistor's grid of the most advanced integrated circuits industrialized in 2007, is only 65 nm, while in the laboratory, widths as low as 6 nm have been obtained. The European platform ENIAC (European Nanoelectronic Interactive Advisory Council) called "More Moore" the tendency which consists in continuing the scaling law to their physical limits.[9] However, these limits approach with great speed, and will probably be reached within ten or fifteen years. The question which arises now is obviously to know if it is possible to pursue Moore's law, and until when?

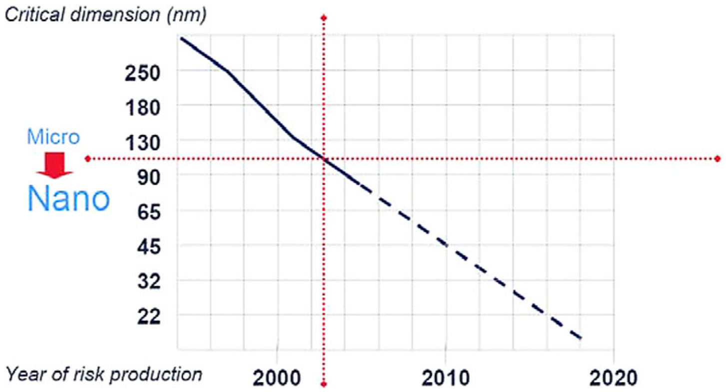

Fig. 5. CMOS technology evolution (from Strategic Research Agenda, ENIAC).

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[8] For a more detailed history on the birth of electronics, see for example Refs. [1–3].

[9] The ENIAC distinguishes two other tendencies, one is called "More than Moore", it consists in integrating "not scalables" technologies like sensors, actuators and other radio frequency devices. It leads to the evolution of the SoC (System one Chip) and of SiP (System in Package). The other, "beyond CMOS", is the field of molecular electronics.

3. Limits of Moore's law

The discussion of the limits of Moore's law is not new. It seemed impossible in the 1980s to cross the wall of the micron, then one thought in the 1990s that the threshold of the 100 nm would constitute a limit; more recently the problem of the lithography was proposed as being an insuperable barrier. Currently, the discussions relate to the fatal threshold of the 10 nm due to the tunnel effect between source and drain…

What is obvious is that the simple shrinking of the geometrical dimensions of the transistor to pass from one generation to the next is no longer possible. Non-geometrical parameters have now to be considered in the 'scaling' of MOS transistors and in the research for their optimal performance. We will examine four of these: properties of materials, structure of the devices, architecture of the grid, and new physical effects emerging on a nanostructure scale.

Several properties of materials are essential for integration. The dielectric properties are important because the insulator of the grid should have a permittivity larger than that of traditional silicon oxide. The current technological node (65 nm) corresponds to a thickness of SiO_2 of only 1.2 nm. The use of 'high k' materials (as HfO_2) makes possible a physical thickness of 3 nm in order to avoid the tunnel effect through the dielectric, while preserving the same electric properties (see, for example, [5]). Then new stack metal/dielectric with high permittivity should spread starting from the 45 nm node. As Gordon Moore said: "*The integration of high-k materials and a metal grid mark the most important change in technology of the transistor since the introduction of the polysilicon grids in the seventies*". Mechanical properties are also important to consider because the introduction of mechanical constraints improve the properties of transport in the channel (see, for example, [6]). Return to germanium, whose mobility is higher than that of silicon, is also considered. The use of new materials does not relate only to the transistors, but also to the interconnections. Copper tends to replace aluminium because it has a lower resistivity (which reduces RC and thus access time) and a better resistance to electromigration (which is a very important point, because at each new generation the reduction of the line section implies an increase of current density which tends to intensify electromigration in the interconnections). The 'low k' materials will soon replace silica and nitride.

The structure of the transistor must evolve to obtain reinforcement from the electrostatic coupling between the grid and the channel. This increase is automatic for bulk MOS transistors thanks to the reduction of the grid oxide's thickness and also by the introduction of metal grids and high-k materials. It can also be done by the introduction of a Silicon-on-Insulator substrate (SOI technologies), or by the modification of the grid architecture (multi-grids devices). A combination of the last two solutions (multi-grid SOI devices) is also to be considered. Various MOS multi-grid transistor architectures are considered: the double-gate structure, the tri-gate structure (FinFET), the pi-gate and omega-gate structures, and even GAA devices (Gate-All-Around), see for example [7].

One of the possibilities to continue the integration of components on a nanometric scale is the introduction of a silicon nanowire, playing the role of the conduction channel; one speaks then about SNWFET devices (Silicon NanoWire FET). Such a nanowire can only have a thousand atoms, even less. So, a quantum modelling, by an ab.initio method, is then possible (see for example [8]). Mesoscopic phenomena appear; thus the more the section of the nanowire decreases, the more the structure of bands moves away from massive silicon: the silicon nanowire becomes a semiconductor with a direct gap and the effective masses of electrons and holes are greater than those in bulk silicon. In addition, in a transistor for which the length of the channel is lower than 10 nm, the transport of electrons is ballistic: their passage from source to drain can be done directly (see for example [9]). The carriers should no longer be represented in terms of particles but in terms of waves. The traditional concept of trajectory has to be replaced by a time dependent quantum state, characterized by a wave function which contains all he possible information on the particle under consideration. The resolution of the Schrödinger's equation shows, for example, that during their transport the electrons coming from the source have a certain probability of being 'reflected' by the barrier.

4. Towards new electronics

The new electronics corresponds to what the ENIAC calls 'beyond CMOS'. It is the domain of wave electronics, of spintronics (the spin becomes the vector of information, replacing the charge), of 'moletronics', 'nanotronics' (where a single electron or single photon is used), of nanomagnetism (which makes it possible to conceive memories without a power supply) and of molecular electronics (where lithography could be replaced by auto-assembling mechanisms).

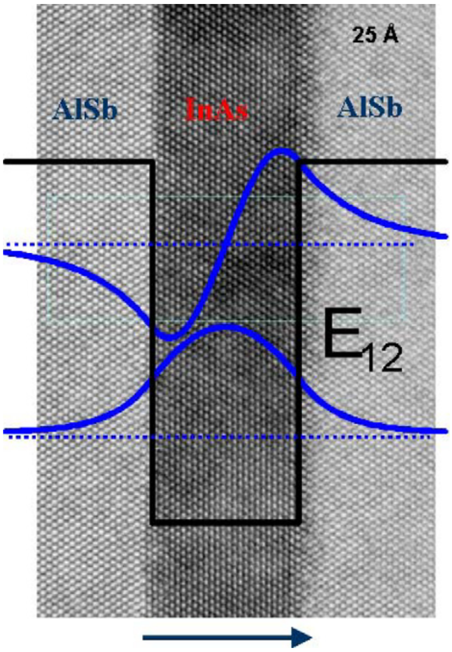

Fig. 6. Elementary structure of a Quantum Cascade Laser.

4.1. Wave and spin based devices

The electron cannot only be represented by an electric charge without dimension, but also by a wave. The control of layers on a nanometric scale, by epitaxy techniques, has allowed the use of the wave properties of electrons for more than fifteen years. This can be illustrated by taking the example of a quantum optronic component: the 'Quantum Cascade Laser' (QCL). Its operation was shown for the first time at the 'Bell Laboratories' in 1994 [10]. This type of laser differs basically from the traditional laser diode. For the latter, the energy gap determines the wavelength of emission of the laser. In a quantum cascade laser, the electron makes an inter sub-band transition inside the quantum well. The quantum well uses a III/V heterostructure, for example: AlSb–InAs–AlSb (as shown on Fig. 6) or $Al_xGa_{1-x}As$–GaAs–$Al_xGa_{1-x}As$. Let us consider the last structure: the thickness t of the intermediate layer (here GaAs) corresponds to that of the well. Because electrons are waves and because the boundary conditions have to be respected, it is easy to show, by the resolution of the Schrödinger's equation, that only the electrons having discrete energy levels can remain in the well. These authorized energy levels (and thus the associated emission wavelengths) depend on two parameters: the stoechiometry (value of x) and the width of the well (value of t), which is typically of the order of some nanometers (for example $x = 0.3$ and $t = 8$ nm correspond to 125 meV or 10 μm wavelength). Thus, we have the equivalent of an artificial atom for which the energy levels were fixed by the parameters x and t. So this technique, consisting in imposing the wavelength emission, is called 'quantum engineering'. The 'cascade' structure of the active zone of these lasers is the second fundamental element which differentiates them from the traditional laser. An electron which makes a transition at the period N emits a photon and is then 'recycled' to make a new transition at the $N + 1$ period. So each electron can emit several photons during its fall in the cascade (to take again the preceding example, if the component is polarized under 3 V one will be able to make emit around 24 photons of 125 meV per electron: 24×0.125 meV $= 3$ V). With this technique there is no longer a limitation for the choice of the emitted wavelength which, in practice, can be fixed between 3 to 100 μm (this last case corresponds to a terahertz emission: 100 μm $\equiv$ 3 THz, see, for example, [11]). Let us note that the dual mechanism is also possible. Quantum wells can also be used to produce quantum detectors leading to the concept of the so-called Quantum Wells Infrared Photodetectors (QWIP). These devices, developed since the end of 1980 [12] are able to detect infra-red radiation in a range going from 3 to 18 μm [13,14].

However, the electron also has a spin. Just as one calls 'electronics' the science and technology bringing into play the electric charge of the electron, one calls 'spintronics' the science and technology bringing into play the spin of the electron. The 2007 Nobel Prize in Physics has been just awarded to Albert Fert and Peter Grünberg "for the discovery of Giant Magnetoresistance" (GMR) which is at the origin of a new scientific and technical field: spintronics.[10] In 1988 Fert and Grünberg each independently discovered GMR [15,16]. The Giant Magnetoresistance is the 'giant' interaction that exists between very thin layers of magnets (of nanometric sizes) and electrons. In spintronics, the control of the electron motion is not the result of their electric charge, as in 'traditional' electronics, but of their spin. Let us consider a conductor in which one inserts a very thin layer of magnetic material (iron for example). Before crossing this thin layer of nanometric size (typically 3 nm), the electrons can be in two opposite states of spin ('up' and 'down'). If the magnetization of the iron layer is directed upwards, only the electrons having a spin 'up' will be able to cross it. Let us insert now, one to two nanometers further, a second layer of iron. If its magnetization is still directed upwards, the electrons will pass, if it is directed downwards, they will not pass. Thus the state of magnetization of the second layer of iron determines the passage or the stopping of the electrons. This passage is not controlled by the use of electric properties, but by the purely quantum property of spin.

Spintronic devices are used in the field of mass storage devices. Since 1998, thanks to the GMR, it is possible to make hard disks with a capacity of 6 Gbit/in^2 ($\sim$1 Gbit/cm^2). This capacity reached rapidly 200 Gbit/in^2 (that is to say $\sim$30 Gbit/cm^2). Recently, IBM scientists announced that they could compress massive amounts of data into a small area, at approximately one trillion bits per square inch (1.5 Gbit/mm^2) or roughly 1 Tbit on a single sided 3.5″ diameter disc. A hard disk of 1 Tbit can contain information equivalent to approximately 2 millions books (with paperback format), or to 2.5 million photographs (of average definition) or to 20 000 CD audio (with MP3 compression) or to 750 hours of video. New techniques, even more powerful, such as Tunnelling Magneto-Resistance (TMR) are under study. Among other applications of spintronics, let us quote MRAM memories (Magnetic Random Access Memory). Today applying an external magnetic field does the commutation of MRAM memory points. With the spin transfer technique it will be possible to commute local memory point without external magnetic field, and also to design reconfigurable logical electronics.

4.2. Molecular electronics

Molecular electronics offers a hope to cross the wall of 10 nm. Its goal is to design electronic circuits using devices based on nano-objects. These nano-objects can be: (i) synthetic molecules; (ii) biomolecules resulting from the natural environment by extraction (they are generally of a big size (1–100 nm) and present a strong faculty of auto-assembly); (iii) metal or semiconductor nanoparticules (e.g. single electron transistors); (iv) nanowires and carbon nanotubes. The stake of molecular electronics is important because it can offer alternative solutions in term of cost reduction, due to the possibility of auto-assembly.

The first step towards molecular electronics was governed thanks to the carbon nanotubes. Sumio Iijima from 'NEC Fundamental Research Laboratory' in Tsukuba fortuitously discovered carbon nanotubes in 1991, where he studied the effects of the vaporization of graphite electrodes by electrical discharge [17]. This discovery of this new allotropic variety of carbon gave a new research direction in the sector of the carbon molecules which were hitherto concentrated on fullerenes. It should be said that nanotubes have exceptional properties. We will present here only some aspects of their electric properties without evoking the mechanical aspects even though these are remarkable. While the Multi-Walls NanoTubes (MWNT) are metallic, the Single Wall NanoTubes (SWNT) are either metallic or semiconductor (according to their chirality). Metallic nanotubes have at the same time an excellent electric conductivity (twice better that of copper) and an excellent thermal conductivity (better than that of diamond). Moreover, the form factor (that is to say the length/radius ratio) of the nanotubes being extremely high (approximately 10^4), electronic transport is 'ballistic'. One can design transistors with carbon nanotubes which resemble conventional MOSFET type transistors, but the silicon channel is replaced by one or more nanotubes which connects the source to the drain. One calls these transistors CNTFET (for Carbon Nanotube Transistor FET). These transistors have a good transconductance and an excellent $I_{\text{On}}/I_{\text{Off}}$ ratio. Pioneer works on CNTFET have been made by Avouris from IBM [18,19] and Dai from Stanford [20]. The performance of these transistors (which can be prepared like p or n transistors), is remarkable and even better (with comparable geometry) that those of 'good' silicon MOSFETs. One can mention the transconductance

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[10] Let us point out what François d'Aubert, then Minister for Research, said during the launching of Minatec on December 16, 2004: "*France is a major actor in the field of the nanosciences and nanotechnologies. It is in our laboratories and thanks to the work of Albert Fert, that Giant Magneto-Resistance was discovered. It makes it possible to carry out magnetic heads, now produced at the rate of 615 million per year.*"

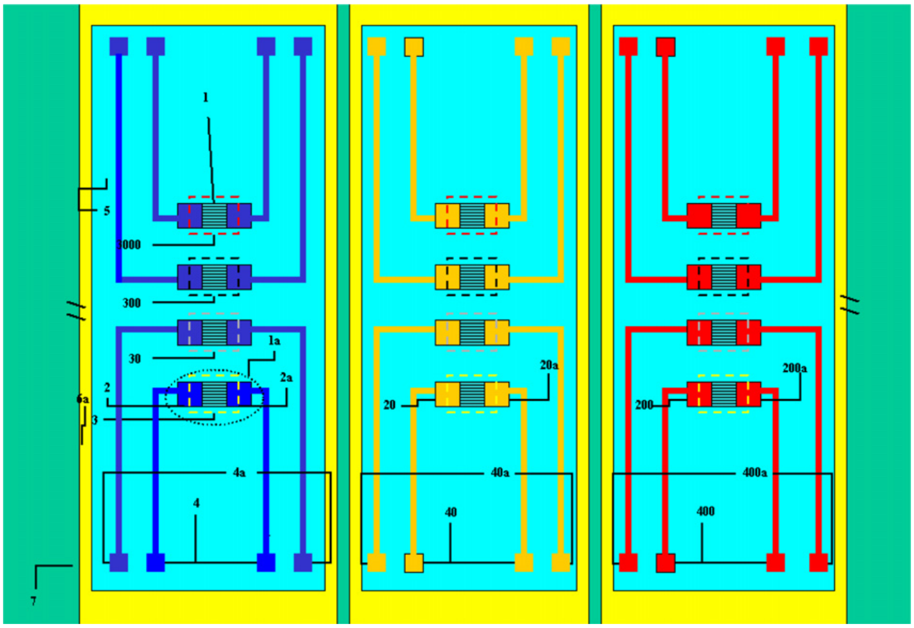

Fig. 7. Matrix of CNT FET for chemical detection.

(6000 S/m or 12 μS/nanotube); the sub-threshold slope ($S = 70$ mV/dec); and the effective mobility (3000 $\text{cm}^2/\text{V s}$) [21]. Let us notice that these transistors do not work exactly as silicon MOSFETs but rather like Schottky barrier transistors: the grid modulates the carrier injection effectiveness at the source level and not the carrier density in the channel (on state of the art on CNTFET properties, see for example [22]).

It is, however, difficult to obtain a high level of integration and so, these transistors are used today individually or with a very low level of integration. Let us note, however, the development, by Hewlett–Packard, of flip-flops allowing the demonstration of a 64 bit CNT memory. It is not certain that one can obtain high-density memories, but other applications using carbon nanotubes transistors are also under study. In a shorter term, carbon nanotubes could be used for interconnection inside integrated circuits [23]. Indeed, vertical connections with large form factor (12/1 or even more) are difficult to realize with traditional methods. Furthermore, reduction of the lateral dimensions of the connections leads to electromigration problems and increase the resistivity of metals (due to the diffusion of electrons at the surface of the conductor). Carbon nanotubes are likely to offer solutions to all these points.

An application with a strong potential is the use of carbon nanotubes transistors for chemical detection [24,25], and Fig. 7. These transistors can be obtained by depositing carbon nanotubes between two gold electrodes above a silicon substrate with a layer of SiO_2. One can notice then, that the $I\text{d}s$ ($V\text{d}s$) characteristic varies in an important way when the transistor is exposed to the presence of a gas. This phenomenon is interpreted as a Schottky effect between the CNT and the metal of the electrode, whose amplitude depends on the type of metal used and the nature of gas. A detection level as low as ppb (i.e. a part per billion or 10^{-9}) has been demonstrated. Each transistor being extremely compact, it is possible to consider, by using a matrix of CNTFET, to detect a set of chemical agents. Let us note that it is also possible to make biological detection by nanotubes [26,27].

Another characteristic of the CNT can be used, namely, the very great form factor conferring to these objects excellent electronic emissivity performances (spike effect). Thus one can potentially use them for a new generation of flat-screens. Motorola has developed a first prototype of such a screen (in 2005), while Samsung demonstrated a 40″ CNT flat screen. One can also make ‘cold cathodes’ [28,29] allowing of new perspective in the field for X rays tubes [30], or electron tubes: high power tube, compact travelling wave tube, THz tubes, and so on.

Let us return to transistors. As we saw, one of the possibilities consists in using a carbon nanotube (CNTFET) as a channel, that is to say a large molecule. So, why not use a ‘traditional’ molecule and use the electronic transport through this molecule? This possibility is explored. For that it is necessary that the linear molecule presents a cloud of delocalized pi electrons. The conductance, as for the CNT, is then a property of the set Metal–Molecule–Metal and

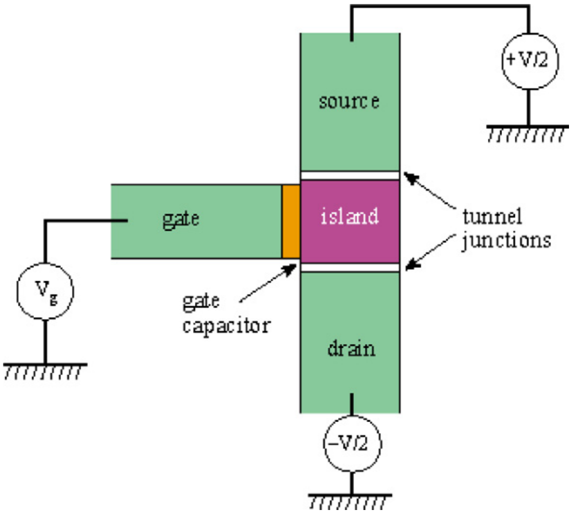

Fig. 8. Schematic of a Single Electron Transistor.

pi delocalized electrons move under the effect of the electric field applied. Indeed, several experiments showed that it is possible to carry out Metal–Molecule–Metal or even Metal–Atom–Metal junctions.

In a more specific way, one can imagine to design memories using a reversible molecule in contact with two metal wire buses ($x\&y$) at right angles. According to the applied voltage to these bistable molecules (rotaxanes or catenanes, for example) the current would pass or not.[11] Hewlett–Packard deposited, in 2000, a patent in this direction. By using such molecules to make an elementary switch for memory, it would be possible to reach a density of 64 memory points per μm^2 [31].

Another concept, called the *Single Electron Transistor* (SET) is also under study (see [32] for concept and [33] for operation at room temperature). In this case, the idea is to use a single electron to convey digital information. A simple calculation makes possible to understand the SET principle. Let us consider a silicon nanostructure with a surface $S = 10\ \text{nm} \times 10\ \text{nm}$ and a thickness $t = 10$ nm. Its capacity is $C = \varepsilon_r \varepsilon_0 S/t$. If one deposits only one electron, having a charge e, on this nanostructure, the voltage varies, $\Delta V = e/C = et/\varepsilon_r \varepsilon_0 S \sim 200$ mV, which is very easily measurable. Let us consider now a more realistic case: a spherical shaped quantum dot of radius r, the capacitance is given by $C = 8r\varepsilon_r$. For typical quantum dot material GaAs we have $\varepsilon_r = 13.2$, which give $C = 1.47 \times 10^{-18} r$ farad, with r in nanometers. When a single electron is added or subtracted, the change of potential is $\Delta V = e/C \sim 0.109/r$ Volts. For a nanostructure of radius $r = 10$ nm, this gives a change in potential of 11 mV, which is again easily measurable.

SET (see Fig. 8) is the simplest device in which the effect of the *Coulomb blockade* can be observed. It consists of two tunnel junctions sharing one common electrode with a low self-capacitance, known as the ‘island’. The electrical potential of the island can be tuned by a third electrode (the ‘gate’), capacitively coupled to the island. A Coulomb blockade is the increased resistance at small bias voltage of an electronic device comprising at least one low capacitance tunnel junction. We illustrate the principle in the case of tunnel junctions with an Insulating barrier between two Normal conducting electrodes (NIN junctions). The tunnelling current is proportional to the bias voltage. The tunnel junction behaves as a resistor with a constant resistance. The resistance depends exponentially on the barrier thickness. Typical barrier thicknesses are on the order of one to several nanometers. Let us note that an arrangement of two conductors with an insulating layer in between not only has a resistance, but also a finite capacitance. The current flow through a tunnel junction is a series of events in which exactly one electron passes through the tunnel barrier (see Fig. 9). The tunnel junction capacitor is charged with one elementary charge by the tunnelling electron, causing a voltage buildup $V = e/C$ (C is the capacitance of the junction). If the capacitance is very small, the voltage buildup can be large enough to prevent another electron from tunnelling. The electrical current is then suppressed at low bias voltages and the resistance of the device is no longer constant. The increase of the differential resistance around zero bias is called the Coulomb blockade.

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[11] Due to a switch effect between two states (insulating and conducting) of the molecule.

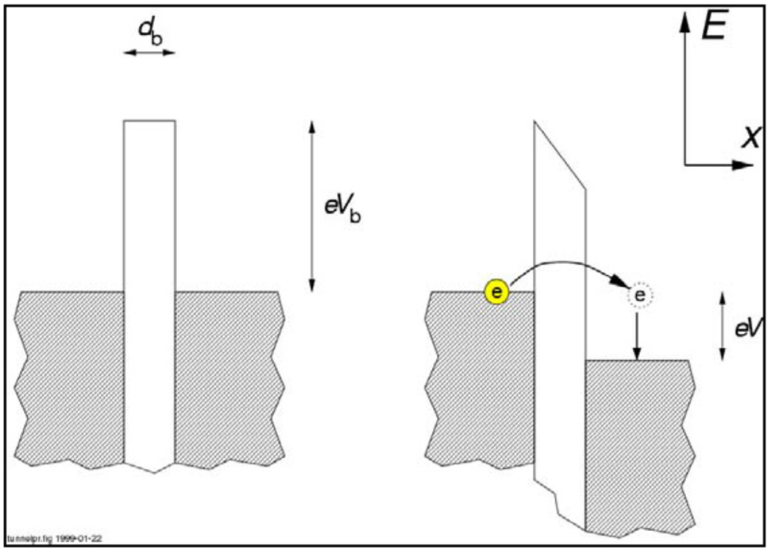

Fig. 9. Schematic representation of an electron tunnelling through a barrier.

5. Conclusion

We have reached the end of our article: what upheavals, what miniaturizations appeared in one century! With the beginning of 21st century, nanotechnologies in general, and nanoelectronics in particular, became a planetary stake. The amounts of R & D brought into play, the competition between the United States, Asia and Europe, the potential technological breakthroughs, the perspective of giant markets, and many more parameters have made this field evolve very quickly. It should be said that the stake is worth the candle: a study of the National Science Foundation states that the world market of products generated by the nanotechnologies will represent, in 2012, 1000 billion dollars! including more than 50% for information technologies. It is difficult to say what will be the nanoelectronics in 2020. Even if the limits of Moore's law are perceptible, the power of the silicon industry made it possible to surmount many difficulties and in the past many alternative technologies remained alternative! Even if a lot of work is carried out in the field of molecular electronics, the gap existing between the demonstrator at laboratory level and the availability of industrial components having a complexity equivalent to several billion transistors and produced at very low cost is truly immense. It is easier to imagine gradual evolutions like the introduction of the carbon nanotubes for connexion inside the devices, the use of optical bus, the development of organic electronics (like RFID), the development of spintronic not only for the increase of the capacity storage of the hard disks, but also for the generalization of the nonvolatile memories, etc. What is sure, it is that the innovating ways are numerous and in these fields, the twenty first century will be no less rich than the twentieth century. For further information we recommend three books, the first deals with the physics at nanometric scale [34], the second deals with the various potentialities of the nanometric world in electronics [35], and the third offers a panorama of the nanotechnologies including economic, political and social aspects [36].

References

[1] W. Shockley, The Path of Junction Transistor, IEEE Transaction on Electron Devices, November 1984 (first ed. 1976).
[2] F. Nebeker, The Electric Century, IEEE Spectrum, June 2000.
[3] R.L. Caen, Note historique, in: Conception des circuits intégrés MOS, Eyrolles, 1986.
[4] G. Moore, Cramming more components onto integrated circuits, Electronics 38 (8) (April 1965) 19.
[5] E.P. Gusev, V. Narayanan, M.M. Frank, IBM J. Res. & Dev. 50 (4/5) (2006) 387–410.
[6] H.S. Yang et al., IEDM Tech. Digest, 2004, pp. 1075–1078.
[7] J.T. Park, J.P. Colinge, IEEE Trans. Electron Devices 49 (12) (2002) 2222–2229.
[8] K. Nehari, N. Cavassilas, J.L. Autran, M. Bescond, D. Munteanu, M. Lannoo, Solid-State Electronics 50 (4) (2006) 716–721.
[9] D. Munteanu, J.L. Autran, Solid-State Electronics 47 (2003) 1219–1225.
[10] J. Faist, F. Capasso, D.L. Sivco, C. Sirtori, A.L. Hutchinson, A.Y. Cho, Science 264 (1994) 553.

[11] S.S. Dhillon, C. Sirtori, J. Alton, S. Barbieri, A. de Rossi, H.E. Beere, D.A. Ritchie, Nature Photonics 1 (2007) 411–415.

[12] E. Rosencher, N. Vodjdani, J. Nagle, P. Bois, E. Costard, S. Delaitre, Appl. Phys. Lett. 55 (1989) 1853.

[13] E. Costard, P. Bois, A. De Rossi, A. Nedelcu, O. Cocle, F.-H. Gauthier, F. Audier, C. R. Physique 4 (10) (December 2003) 1089–1102, (14).

[14] A. Nedelcu, E. Costard, P. Bois, X. Marcadet, Infrared Physics & Technology 50 (2–3) (April 2007) 227–233.

[15] M.N. Baibich, J.M. Broto, A. Fert, F. Nguyen Van Dau, F. Petroff, P. Etienne, G. Creuzet, A. Friederich, J. Chazelas, Phys. Rev. Lett. 61 (1988) 2472.

[16] P. Grünberg, et al., Phys. Rev. B 39 (1989) 4828.

[17] S. Iijima, Nature 354 (1991) 56.

[18] P. Avouris, Accounts Chem. Res. 35 (2002) 1026.

[19] J. Knoch, R. Martel, V. Derycke, S.J. Wind, P. Avouris, IEEE Transactions on Nanotechnology 1 (4) (December 2002) 184–189.

[20] H. Dai, Accounts Chem. Res. 35 (2002) 1035.

[21] A. Javey, et al., Nature Materials 1 (2002) 241.

[22] H. Dai, A. Javey, E. Pop, D. Mann, W. Kim, Y. Lu, Electrical transport properties and field effect transistors of carbon nanotubes, Nano: Brief Reports and Reviews 1 (1) (2006) 1–13.

[23] J. Li, Appl. Phys. Lett. 82 (2003) 2491.

[24] J. Kong, N.R. Franklin, C. Zhou, M.G. Chapline, S. Peng, K. Cho, H. Dai, Nanotube molecular wires as chemical sensors, Science 287 (2000) 622–625.

[25] P. Bondavalli, P. Legagneux, D. Pribat, Gas fingerprinting using carbon nanotubes transistors arrays, in: Nanotech07, Santa Clara, 21–24 May 2007.

[26] P. Qi, O. Vermesh, M. Grecu, A. Javey, Q. Wang, H. Dai, S. Peng, K.J. Cho, Toward large arrays of multiplex functionalized carbon nanotube sensors for highly sensitive and selective molecular detection, Nano Lett. 3 (3) (2003) 347–351.

[27] R.J. Chen, H.C. Choi, S. Bangsaruntip, E. Yenilmez, X. Tang, Q. Wang, Y.-L. Chang, H. Dai, An investigation of the mechanisms of electronic sensing of protein adsorption on carbon nanotube devices, J. Am. Chem. Soc. 126 (5) (2004) 1568.

[28] K. Teo, E. Minoux, L. Hudanski, F. Peauger, J.-P. Schnell, L. Gangloff, P. Legagneux, D. Dieumegard, G. Amaratunga, W.I. Milne, Microwave devices: Carbon nanotube as cold cathodes, Nature 437 (2005) 968.

[29] E. Minoux, O. Groening, K.B.K. Teo, S.H. Dalal, L. Gangloff, J.-P. Schnell, L. Hudanski, I.Y.Y. Bu, P. Vincent, P. Legagneux, G. Amaratunga, Achieving high current carbon nanotube emitter, Nano Lett. 5 (2005) 2135.

[30] J. Zhang, G. Yang, Y. Cheng, B. Gao, Q. Qiu, Y.Z. Lee, J.P. Lu, O. Zhoua, Stationary scanning x-ray source based on carbon nanotube field emitters, Appl. Phys. Lett. 86 (2005) 184104.

[31] C.P. Collier, et al., Science 289 (2000) 1172.

[32] M.H. Devoret, D. Esteve, C. Urbina, Nature 360 (1992) 547.

[33] L. Zhuang, L. Guo, S. Chou, Appl. Phys. Lett. 72 (1998) 1205.

[34] C.P. Poole Jr., F.J. Owens, Introduction to Nanotechnology, Wiley, 2003.

[35] M. Wautelet, et al., Les Nanotechnologies, Dunod, 2006.

[36] D. Luzeaux, Th. Puig, A la conquête du nanomonde, nanotechnogies et microsystèmes, Editions du Félin, 2007.