Chapter 9

Emerging quantum devices

Conventional microelectronic technologies have moved swiftly but continuously - based on a top-down approach - towards the nanometer range. Many commercial microprocessors or memories are now manufactured with minimum dimensions in the 20 nm range. There have been changes in some physical features but basically the architecture of the components remained the same. Outstanding progress in the technology domain has given the possibility to engrave silicon at dimensions which one could not imagine before because of physical limitations. Reducing even further the size of the components poses new problems because the physics can change. Classical physics has to be replaced by quantum mechanics and new phenomena appear while classical ones disappear. We shall now have a quick look to these emerging technologies in the information and communication domain.

The electron, an elementary particle

The electron is an elementary particle with a negative charge $-e$ *(where* $e = 1.6 \times 10^{-19} C$ *is the elementary charge, that is the smallest charge which can be experimentally observed). It has an intrinsic angular momentum called spin which is equal to*[a] $s = \frac{1}{2}\hbar$*. Spin is a pure quantum property of elementary particles although people try to sometimes make some representation in our classical world. In this case one could think that the electron rotates around one of its symmetry axis like a top. This is of course not true in the real world because an electron is a point particle. Furthermore, even if it would be a tiny sphere, such an object cannot rotate in the quantum world.*
Classically, the projection of the angular momentum (which is a vector) on an arbitrary axis takes values varying continuously between a minimum and maximum value. This is no longer true in the quantum world where discrete values are only possible. Therefore, for the electron, its spin is a vector with only two possible projections on a given axis which we shall refer to as z : $s_z = +1/2\ \hbar$ *and* $s_z = -1/2\ \hbar$*.*
Because of its spin, a magnetic moment, which is a vector, is associated to each electron. Its value is proportional to the spin but points in the opposite direction. Similarly to the spin, the magnetic vector has only two possible projections on a given axis.

[a] $\hbar$ is the Planck constant (h) divided by 2π ($\hbar = \frac{h}{2\pi}$). It is often used as a unit to measure angular momenta. In this case one says that the spin of an electron is $\frac{1}{2}$. Although it is currently said that the spin of an electron is $s\hbar$ or s in units of $\hbar$, this is not the length of the spin vector because of quantum mechanical reasons. Actually the length of the spin vector is equal to $\hbar\sqrt{s\,(s+1)} = \sqrt{3}\hbar/2 \approx 0.866\hbar$. However, the projection of this vector on the z axis can take two values: $\pm\hbar/2$.

Shrinking the dimensions of micro-electronic components has a limit. Below some size the physics governing processes changes and prevent the component to work in the same way as it was the case for a larger size. We are going in a new physical world with surprises and we shall touch a little bit this new area now.

9.0.1 Beyond the quantum wall

All our electronic devices are based on the transport of electrons. However, moving electrons cost energy which is usually supplied by the grid or the battery of the device. Information can be carried from one place to the other (within the digital circuits of a computer, for example) or treated (such as switching a bit from one to zero, for example) thanks to electric signals which are generated by transport of electrons. For instance, a MOSFET (Metal Oxide Semiconductor Field Effect Transistor) which is a transistor for amplifying or switching electronic signals, needs about 1,000-10,000 electrons to switch from the insulating to the conducting state. Common sense tells you that if you could do the same job with fewer electrons you would need less energy to do it. This is what

is observed as electronic circuits are shrunk in successive generations of microprocessor technologies. They consume less energy because transistors are smaller and need fewer electrons to function. That is the reason why the same processor engraved with different feature size has the different energy consumption to do the same job. The ultimate goal would be to be able to switch a transistor with a single electron. This is possible as we shall see below but a different physics is involved and the transistor has a different behavior compared to common transistors. Using fewer electrons to do the same function means also that the component is more sensitive to thermal background

9.0.2 Coulomb blockade

A thin insulating layer (one to several nm thick) between two conducting electrodes is a *tunnel junction*. In classical physics, no electron can flow through the insulating layer: it acts as a barrier against electron flow. However, quantum tunneling takes place in the case of a thin insulating layer (cf. chapter 3) and electrons can go through the barrier. Applying a bias voltage between the two conducting electrodes generates an electron current and a tunneling current which turns out to proportionally increase with the bias voltage. This means that the insulating layer acts as a resistor. But putting an insulating layer in between two conductors is a capacitor. The thin layer is just the dielectric of the capacitor. Actually, the thin layer has a resistance and a capacitance.

We know that the electric charge is quantized and that e is the smallest amount of charge. Electrons have a $-e$ charge while protons a $+e$ charge. An electric current is just a flow of electrons. If the number of electrons is large, the flow can be considered as continuous. However, for small flows, the quantization of the charge can be seen.

Let us now consider a tunnel junction (thin insulator layer separating two conducting electrodes) at low temperature (typically below 1 Kelvin) and assume that the net charge on the electrodes is zero (top figure 9.1). Such a system is in its lowest energy state. Suppose that one electron is tunneling from left to right through the barrier. In the final state there will be $-e$ charge on the right and $+e$ charge on the left (bottom in figure 9.1). The $+e$ charge means actually that a hole is left as the electron as moved through the barrier. Between the initial and the final state there is a difference of $2e$. Tunneling an electron across the junction increases the energy of the system (the results are such that we have charged the capacitor having the thin layer as dielectric). The voltage difference U induced by the tunneling of an electron is equal to $U = e/C$, where C is the capacitance and e the elementary charge. If the capacitance is very small, U can be large enough to prevent any other electron from tunneling.

We would get a similar situation by considering tunneling of an electron from right to left. Consequently, if no external energy is provided to the tunnel junction, such a tunneling effect is impossible: This is the essence of *Coulomb blockade*. Since there is no electrical current at low bias voltage, the resistance of the thin layer is not constant.

We shall now investigate how it is possible to move an electron across the barrier at no energy cost. For that we shall consider the same schematic device as in figure 9.1 but where the initial electrodes have a charge equal to $e/2$. It should be noted that the charge of a particle can only be an integer number of the elementary charge e. However, in a metal the motion of electrons and vibrations of ions induces on the electrodes a fluctuating charge which is not necessarily an integer of the elementary charge and varies continuously. In other words, the average value of an uncharged electrode is zero but fluctuations around

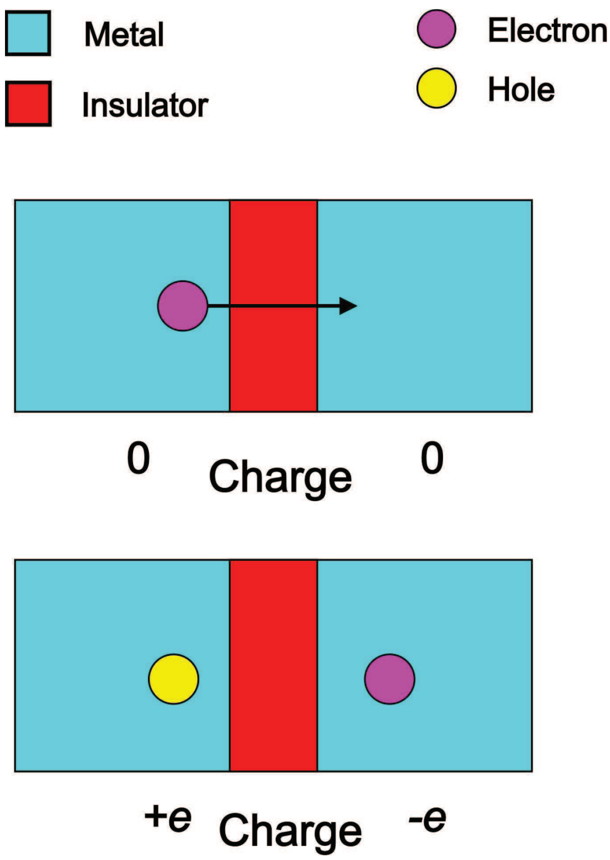

Figure 9.1: *If the two electrodes (in blue) are not charged electrically, an electron cannot spontaneously go across the insulator junction (in red) because it costs a lot of energy. Inspired from R.Turton, The Quantum dot, W.H.Freeman and Company Limited, 1995.*

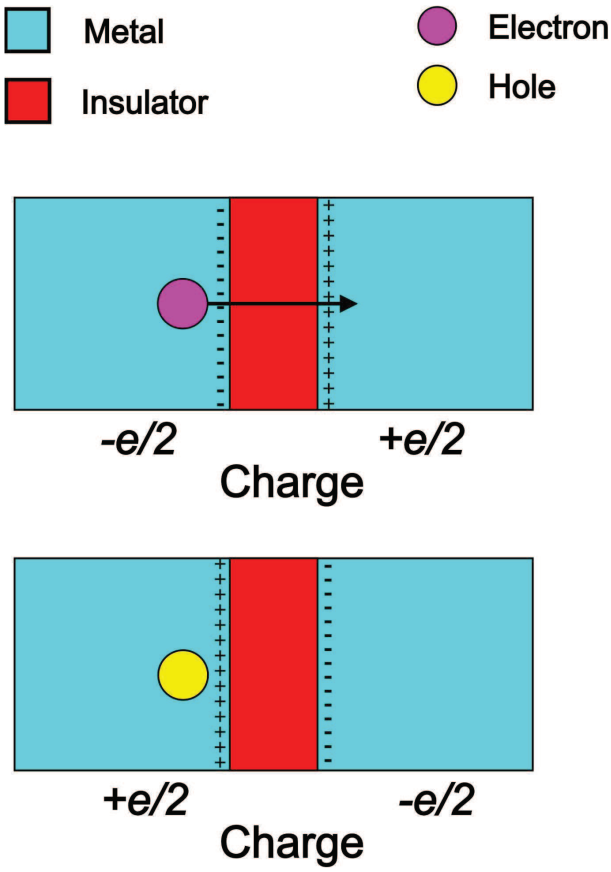

Figure 9.2: *If the two electrodes (in blue) are charged electrically with e/2, an electron can go across the insulator junction (in red) because it cost no energy. Inspired from R.Turton, The Quantum dot, W.H.Freeman and Company Limited, 1995.*

this average value make the charge of the electrode to change as a function of time. This occurs for both electrodes. The situation shown on top of figure 9.2 can be reached during these fluctuations. In this case an electron can go across the insulating junction because no energy is required. Look indeed at the situation before and after the electron transfer in figure 9.2. The charge on the electrodes has just changed sign but the energy of the system remains the same. One electron can go across but not two at the same time otherwise energy would be needed.

A little more complicated device is shown in figure 9.3. Here, a small metallic dot (central electrode) is separated from external electrodes by two insulator junctions. A gate (in black) is used to apply an external voltage. Energy can be injected into the device and the charge in the dot can be externally controlled. If there is no charge in the dot, the Coulomb blockade mechanism prevents any electron to go across the junctions. Applying an external voltage allows to change this charge and when we get the situation shown in part (3) of the figure we trigger the mechanism discussed in figure 9.2. A second electron can come only if this electron has crossed the second junction using the same mechanism. Such a device allows electrons to go across the central electrode one by one. For this reason one has to deal with a correlated tunneling mechanism.

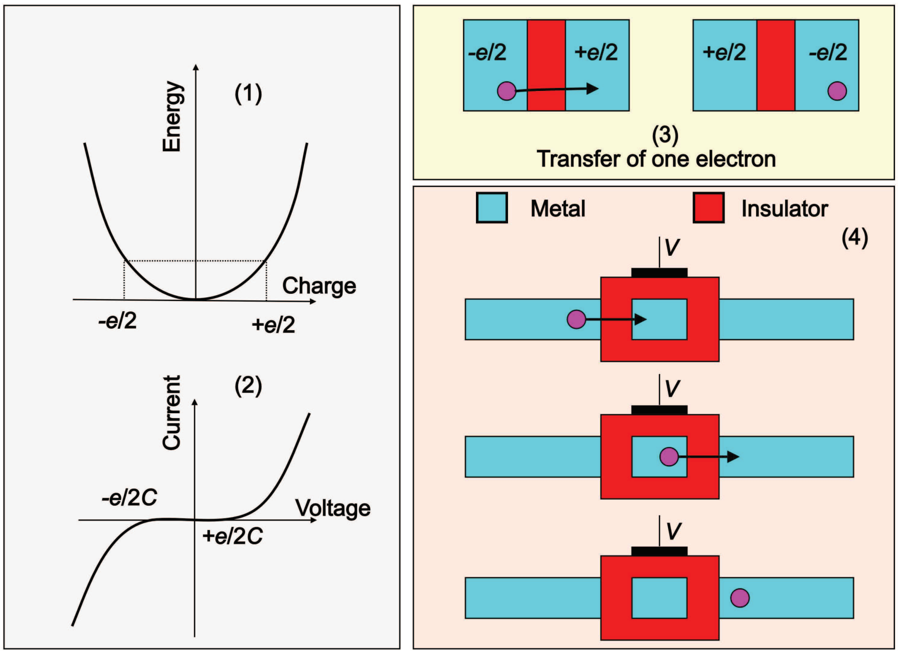

Figure 9.3: *About the 3 parts (1), (2) and (3) of the figure. (1) energy as a function of charge of system (3). (2) Current as a function of the voltage of system (3). (4) Device allowing the electrons to pass one by one (correlated tunneling). Courtesy of C.Ngô and H.Ngô, physique des semiconducteurs, Dunod, 2007.*

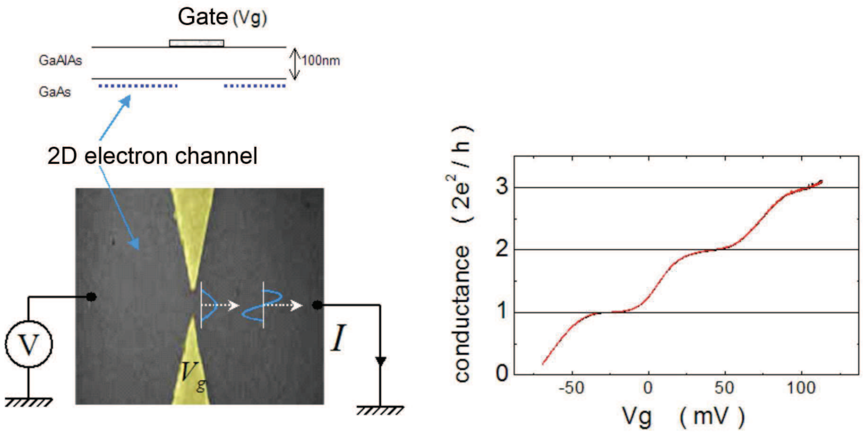

Figure 9.4: *The field effect of two grids, manufactured by nanolithography and evaporated above the surface of a conductor containing an electron layer, can be used to define a constriction of adjustable width. Conductance measures the transmission of electronic modes. Each one has two spin projection possibilities. By increasing the bias voltage, one can see in the figure that the number of modes increases from zero to three. The transmission of a mode is complete when a plateau is reached. Each plateau is an integer multiple of the quantized conductance* $\frac{2e^2}{h}$*. The factor 2 comes from spin degeneracy. Courtesy of CEA. Clefs CEA n° 52.*

Conductance quantization

In figure 9.4 is shown a two-dimensional electron device fabricated by electron lithography. It is basically an electron waveguide with a constriction of submicron length and a width of the same order as the electron wavelength. The constriction of the device can be continuously changed using the field effect of a gate (see figure 9.4). If the width of the contact point is much smaller than the electron wavelength no electron mode is transmitted and the conductance is equal to zero. When the width of the contact point is equal to half the electron wavelength, a first mode is transmitted but the others are reflected. As a consequence, one reaches a plateau in the evolution of the conductance as a function of the gate voltage. The value of this plateau is the quantum of conductance. It equals to 2 times the electron charge divided by the Planck constant. The factor of 2 arises from the 2 possible projections along an axis of the spin of the electron (spin degeneracy). Increasing the gate voltage increases the number of modes that can be transmitted. In the figure, up to 3 modes are transmitted.

9.0.3 The single electron transistor

A transistor is a 3-terminal device which has several applications such as signal modulation, amplification, voltage stabilization, etc. Depending upon the type of the transistor,

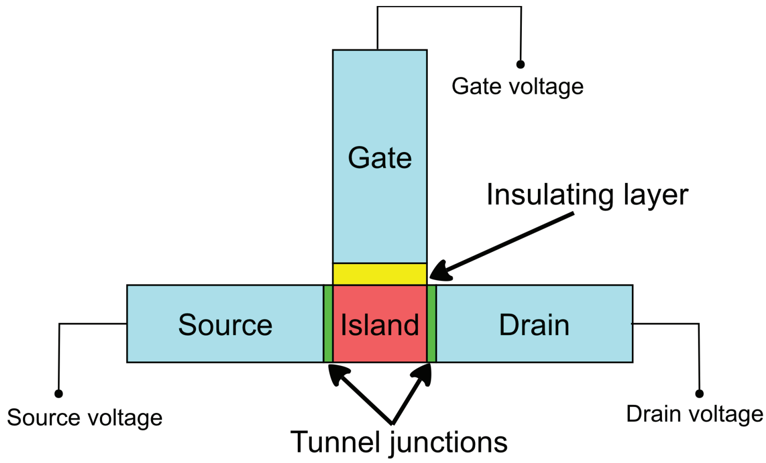

Figure 9.5: *Principle of a single electron transistor. An island (quantum dot, for example), is separated from the source and the drain by a very thin layer acting as a tunnel junction. The gate electrode is separated from the island by a thick material preventing electrons to tunnel through. The gate influences electrostatically the island.*

an input current or an input voltage allows to control the current supplied flowing through the device.

The Coulomb blockade effect is observed in the single electron transistor device. The idea of making a single electron transistor goes back to the late 1980s. At that time, the technology node was close to 1μm and about 10,000 to 20,000 electrons were moved during a switch on/off of a MOSFET transistor. Reducing this number of electrons reduces the energy consumption. The consequence of shrinking the dimensions of the transistor down to the 100 nm is to reduce the number of electrons involved to switch the transistor to a few hundreds. It allows also to increase the density of transistors per unit area. The limit of the game occurs when only one electron is involved. However, we are now going into a new domain of physics where tunneling effect can play a role.

A single electron transistor is similar to a MOSFET but functions differently. It is a switching device that controls electron tunneling to amplify current. It consists in (figure 9.5) a source, a drain and a very small island of a few nanometers or less built on a semiconductor substrate. The source and the drain are electrically isolated from the island with a very thin layer of silicon oxide playing the role of a tunnel junction. A tunnel junction consists of two pieces of metal separated by a very thin insulator (typically about 1 nm thickness).

An example of single electron field-effect transistor is displayed in figure 9.6 as it is observed using imaging techniques.

A gate allows controlling the flow of electrons through the island by electrostatic influence. Indeed, the material separating the gate from the coulomb island is too thick to be a tunnel junction. The gate is a conductor isolated from the device by an insulator. An electron can only tunnel from the drain to the island and then from the island to the drain but the coulomb blockade may hinder this process which can be monitored by the bias applied to the gate. The number of electrons in the island can be precisely fixed and their flow in and out perfectly controlled. Such a transistor works like a leaky faucet drip where a drop represents an electron. The tap controls the number of drops which flows out. What is different in a single electron transistor is that the electrons flow one by one

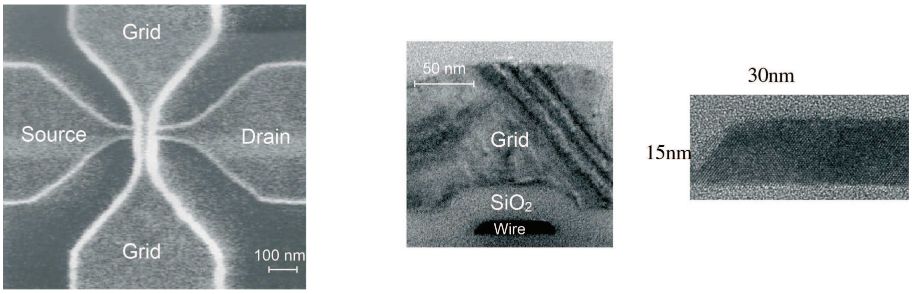

Figure 9.6: *Picture of a single electron field-effect transistor. Courtesy of CEA. Clefs CEA n°52.*

and at fixed values of the bias applied to the gate. Indeed, tunneling is a discrete process where the electric charge that flows through the tunnel junction occurs in multiples of the charge of electrons. The characteristic curve correlating the bias to the current is no longer an increasing continuous line but the series of discontinuous steps.

A single electron transistor has to be operated at very low temperature in order to get rid of thermal background which would make otherwise thermal excitations and make the device unusable. Other free electrons may also exist and travel over space (we feel static electricity for example with some of our clothes when they rub on a plastic material). In order to be able to use such a device at ambient temperature a very small island (smaller than about 1 nm) should be made which is difficult today to manufacture in a reproducible manner at an industrial scale. Furthermore, the function done by the single electron transistor is different from the one provided by a MOSFET. This requires having different architectures to treat information. So far the single electron transistor is still studied in the laboratory and not yet ready for industrial use. Single electron transistors have been made using metal, semiconductor, carbon nanotubes and molecules.

9.0.4 Applications of single electron transistors

Single electron transistor is an emerging technology. It is still a tool in research and has no extensive applications. In order to be operated at room temperature, the island should have sub-nanometer dimensions. This is a difficult challenge at the industrial level especially to produce quantum dots in a reproducible manner. Small variations in shape can lead to large variations. Larger dimensions of the island require to operate at low temperature otherwise the thermal background prevents using the device. There are also other problems such as the tunneling of several electrons through different barriers at the same time or the background charge coming for example from impurities.

Nevertheless single electron transistors can be useful for specific applications in research. Figure 9.7 shows some of them.

A single electron transistor can be used as a very sensitive electrometer allowing to detect extremely low DC currents ($\simeq 10^{-20}$ A). It can also be helpful in standards (current, temperature). Programmable logic is also possible thanks to the non-volatile memory function of a single electron transistor and voltage state logics is also an application because the gate voltage controls the current flowing between the source and the drain part of the transistor.

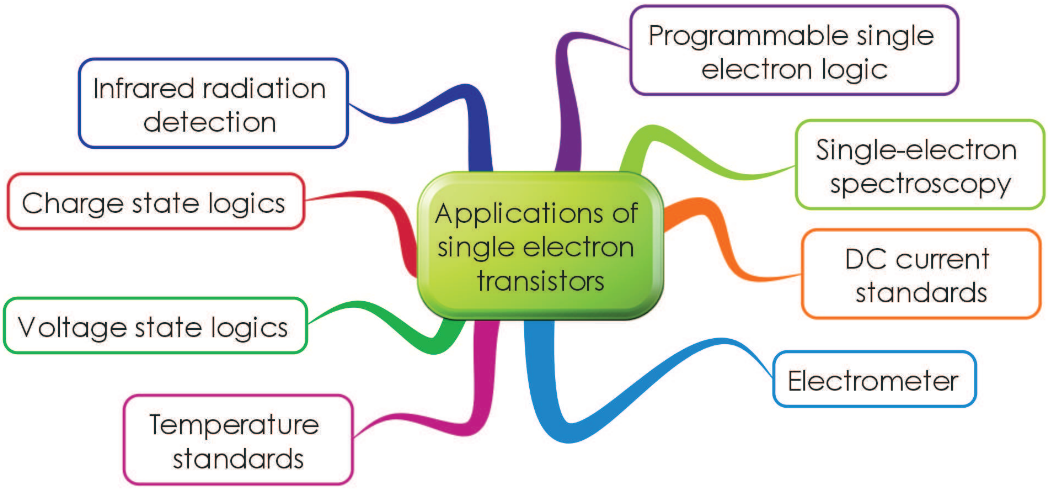

Figure 9.7: *Possible applications of single electron transistors. According to O.Kumar and M.Kaur, Int Journ of VLSI design & communication systems (VLSICS) Vol 1, 4, 2010.*

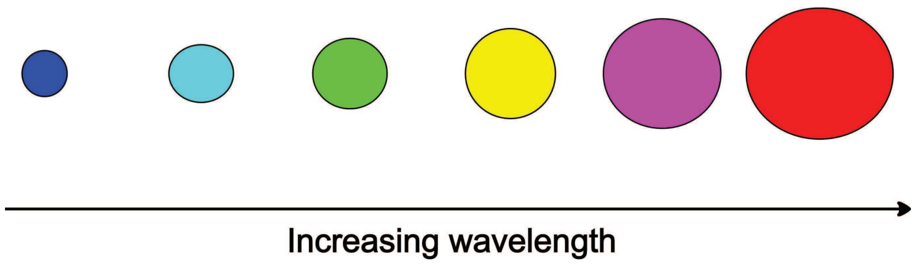

Figure 9.8: *Schematic illustration of the size influence on quantum dot emission. As the size of the quantum dot increases, we move from blue to red.*

9.0.5 Quantum dots

Semiconductor quantum dots are nano-objects where electrons can be confined in a nanoscale volume. A nanoscale cubic box was an academic example discussed decades ago in quantum mechanics lectures to illustrate the appearance of discrete energy levels for a particle enclosed in a cube of very small dimensions. Two-dimensional or one dimensional confinement is also possible. The nice thing is that these academic examples are now real objects that can be manufactured in the laboratory.

A quantum dot can be seen as an artificial atom, as far as its optical properties are concerned. Indeed; the energy level separation is inversely proportional to the square of the dimension of the confinement. Since the energy difference between two energy levels is directly connected to the wavelength absorption of the light, the color of a solution of quantum dots can be adjusted on demand. Similarly, exciting a quantum dot gives definite wavelength emission and therefore a specific color.

Figure 9.8 shows a schematic representation of the color emitted by excitation of quantum dots of different size. As the size increases we move from the blue region of the optical spectrum to red.

Quantum dot is a term usually reserved to semiconducting materials. Quantum dots belong to the wider domain of nanoparticles which can be made out of different materials: metals, insulators, organic materials, *etc.* Nanocrystals correspond to an inorganic crys-

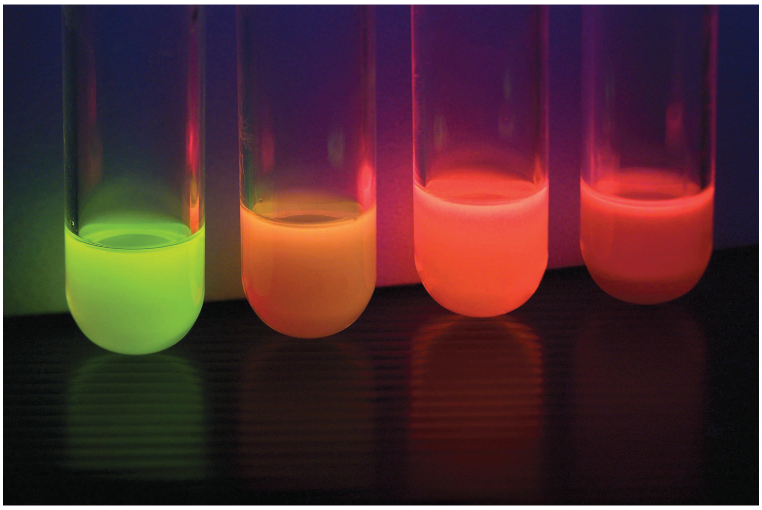

Figure 9.9: *Semiconductor nanocrystals of different sizes illuminated with ultraviolet light. Courtesy of CEA. Clef CEA n°52.*

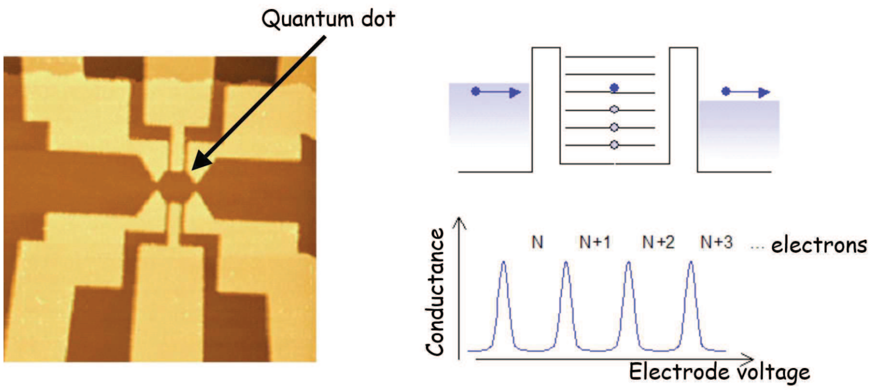

Figure 9.10: *Quantum dot separated from the contacts by a tunnel barrier. The conductance as a function of the gate voltage shows peaks corresponding to the situation where an electron arrives into the quantum dot. Courtesy of CEA. Clefs CEA n°52.*

talline nanosized material. Nanocrystals can be made using a bottom-up manufacturing.

Atoms have discrete energy levels while semiconducting crystals have bands of energy. Semiconductor nanocrystals are intermediate structures and for that reason are called are called *artificial atoms*. It is possible to tailor their optical properties in such a way that they emit in the visible region or in the infrared region by choosing their geometrical dimension. As an example, figure 9.9 shows semiconductor nanocrystals of different size illuminated with ultraviolet light.

Figure 9.10 shows a real example of what has been presented in figure 9.3. A quantum dot is separated from metallic contacts by a tunnel junction. Confinement gives discrete energy levels (top right part of the figure). An electron can go across the barriers if its energy coincides with one of the energy levels. The energy levels can be changed continuously by changing the gate voltage. The Coulom b blockade mechanism discussed above prevents to have several electrons at the same time in the quantum dot. As a result, the conductance shows resonance peaks.

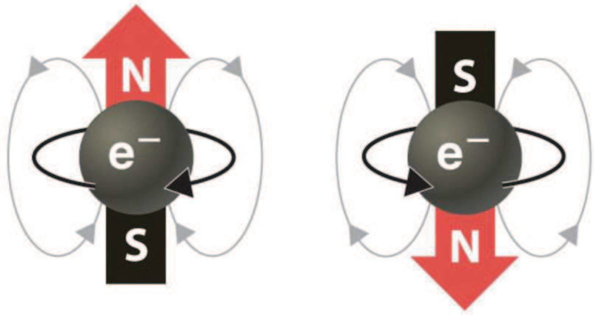

Figure 9.11: *An electron e^- in a magnetic field has two possible orientations associated with different energies, one called spin-up, aligned with the magnetic field, and one with spin-down (anti-parallel to the magnetic field).*

9.1 Spintronics

Electronics devices exploit usually the transport of electric charges. Semiconductor devices are based on the transport of electrons (negative charges) and holes (positive charges arising actually because of a missing electron). Spintronics, called also *spin electronics*, exploits - in addition to the charge of the electron -, its intrinsic spin and the associated magnetic moment to develop electronic devices. The nice thing with the spin of an electron is that it can be oriented in one direction or the other. This means that the projection of the spin vector, measured on an axis, can have a different sign: $s_z = +1/2$ $\hbar$ or s_z =-1/2 $\hbar$ (Figure 9.11). One usually says that we a have a spin-up or spin-down, depending on the sign of the projection with respect to the orientation of the spin vector. Exploiting the spin of an electron rather than its charge to carry or store information has advantages in terms of speed or energy consumption, for example.

The giant magnetoresistance (GMR) is a quantum effect observed in film structures made of alternating ferromagnetic and non-ferromagnetic material layers. The thickness of the layers is typically of the order of 1 nm. This effect has been simultaneously discovered in 1988 by Albert Fert and its team in France, and by Peter Grünberg and its team in Germany. They awarded for this discovery the Nobel Prize in 2007.

Magnetization

Spins can arrange in many different ways depending upon the external condition. If they are free to move at ordinary temperature, they are distributed at random as it is illustrated in the left hand part in figure 12. Applying a strong external magnetic field directed upwards will align these spin as shown in the right hand part of figure 9.12. In a solid-state material, the spin can be oriented at random in a nonmagnetic material or aligned in a magnetic material (figure 9.13).

For the sake of simplicity we shall consider only a stack of 3 layers as displayed in figure 9.14: a non-magnetic tunnel barrier (in the order of about 1 nm thickness) sandwiched between two ferromagnetic layers (in real experiments, about 10 layers or more can be used). It turns out that the electrical resistance depends strongly on whether

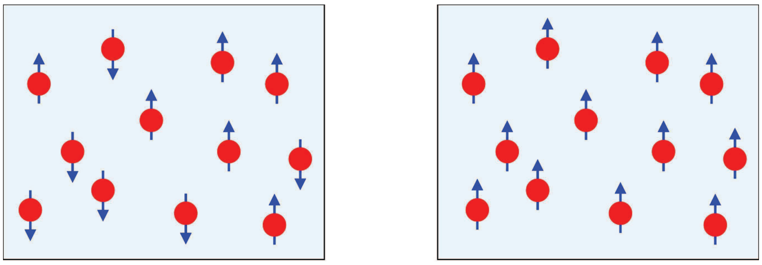

Figure 9.12: *In the left hand part, spins are oriented at random while, in the right hand part, they are aligned along a strong applied external field. Inspired from S. D. Sarma, Spintronics, American Scientist, Vol 89, 516, 2001.*

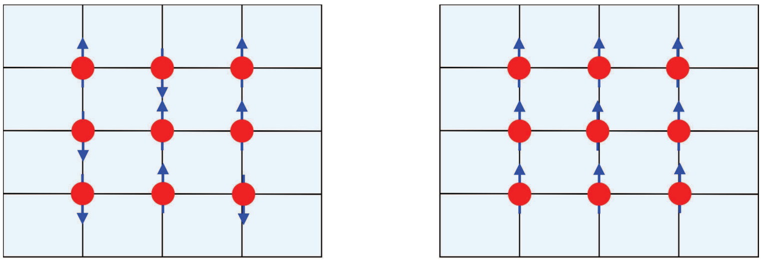

Figure 9.13: *In the case of a crystal where the spins are located at the sites, the spins can be oriented at random in the case of an unmagnetized material or aligned if the material is magnetized. Inspired from S.D.Sarma, Spintronics, American Scientist, Vol 89, 516, 2001.*

the magnetization of adjacent ferromagnetic layers is parallel or antiparallel (Figure 9.15, top and bottom). When the magnetizations are parallel, the magneto-resistance is small *i.e.* high spin current, while it is larger if they are antiparallel (low spin current). This phenomenon is basically used in hard disk drives.

Exploiting the spin of an electron rather than its charge to carry or store information has advantages in terms of speed or energy consumption, for example.

Main fields of applications and new directions are the following:

- spin for storage and reading information
- spin for memory, reading and writing (spin-RAM)
- spin field-effect and tunnel junction devices
- spin optoelectronics
- spin galvanics
- spin quantum computing

We are acquainted to use devices using a magnetic field to control the magnetization orientation of materials and by this process the information stored at that point. Other possibilities of control are now possible with spintronics. They are indicated in figure 9.16.

In addition to magnetic field control, it is also possible to control via spin-polarized electric currents, electric fields or photonic fields. This opens a large number of possible

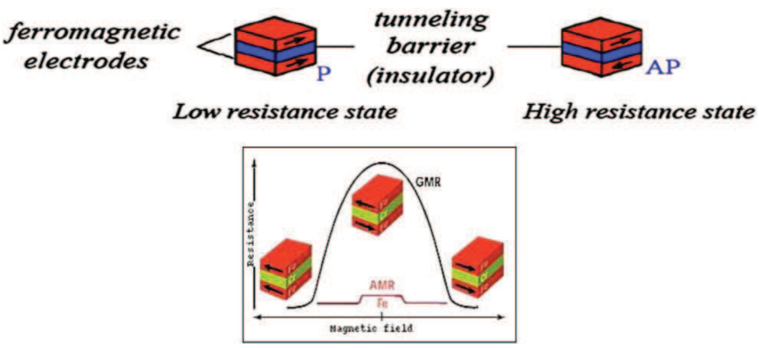

Figure 9.14: *Schematic illustration of magnetic tunnel junction of two ferromagnetic layers separated by a thin barrier layer [A. Fert, Thin Solid Films 517, 2 (2008)] (left); magnetoresistance in dependence of external magnetic field (right).*

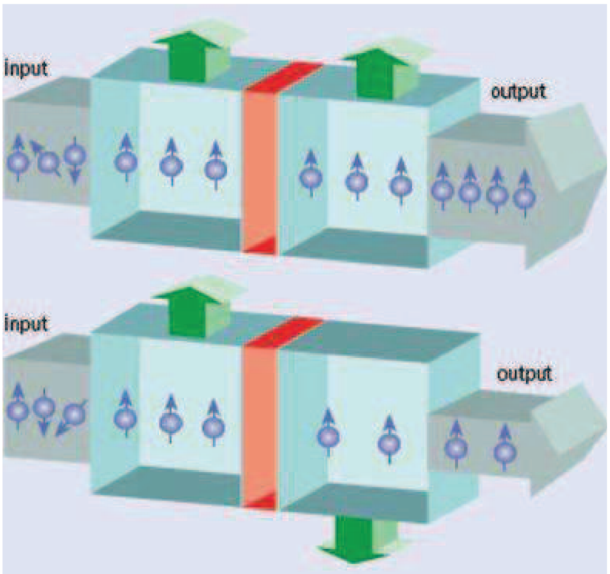

Figure 9.15: *Illustration of magnetic tunnel junction composed of two ferromagnetic layers separated by a thin barrier layer (red). When the magnetization of the two ferromagnetic layers is parallel, spin-up electrons can tunnel through the barrier in the second ferromagnetic layer (top). When the two layers are anti-parallel, however, tunneling is suppressed (bottom).*

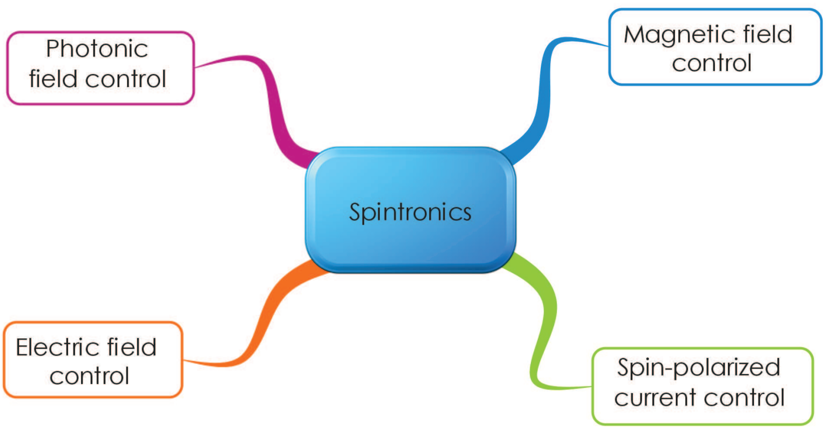

Figure 9.16: *Sectors where spintronics can play a role.*

applications. For example, it is possible to use a spin-polarized electric current to switch the magnetization of a nanoscale memory cell. Electric fields can change the magnetic anisotropy of ultrathin structures. Ultrafast light pulses are another way to switch the magnetization of nanoscale materials.

Because spintronics devices are very small it is possible to study ultrafast phenomena. This is interesting in the domain of imaging and kinetic studies at a scale of picoseconds or femtoseconds.

Spintronics can be based on semiconductors or metals. Several applications using metal spintronics exist, especially in the storage domain. However semiconductors spintronics offers a lot of potentialities because of their possible integration in semiconductor electronics.

9.2 Quantum computing

Quantum computing uses the properties of atoms, molecules, photons, *etc.* to perform processing and memory tasks. Today's computers manipulate bits which can be in two states labeled 0 or 1. Quantum computers, which are for the moment at the research stage, use qubits (quantum bits) which are not limited to two states. All the possibilities, between 0 and 1 are in principle possible. Indeed, a qubit, which is the unit of quantum storage information, can be a superposition of the two basic quantum states. Starting from quantum states, multiple states can be made giving the potential to manufacture much more powerful computers than today's supercomputers.

Quantum entanglement

If a quantum system like a particle is in an eigenstate, a measurement of an observable quantity can be predicted for sure. For example if we have prepared a particle of spin $\frac{1}{2}$ in a state where the projection of the spin is $+\frac{1}{2}$, we will get for sure $+\frac{1}{2}$ if we measure this quantity. Generally a system is not in an eigenstate and we can just say that there is some probability to measure a given value of the observable. In the example taken above, if we have a particle with a spin $\frac{1}{2}$ but we do not know the spin projection and if there is no external applied magnetic field, then if we measure this projection it can be either $+\frac{1}{2}$ or $-\frac{1}{2}$ with the same probability. It should be noted that if we have measured $+\frac{1}{2}$ once we shall measure $+\frac{1}{2}$ for any subsequent measurement.
*If we now consider two independent particles of spin $\frac{1}{2}$ **A** and **B**, and no external magnetic field applied, we can measure, independently a projection $+\frac{1}{2}$ and $-\frac{1}{2}$ with an equal probability. A measurement of the spin projection of **A** is completely independent of that of **B**.*
*Let us now prepare initially a system of two particles **A** and **B** in such a way that the total spin of the system is equal to zero. This means that if the projection of the spin is $+\frac{1}{2}$ for **A** it should be $-\frac{1}{2}$ for **B** and vice versa. The sum of the total projections should be zero indeed. We suppose that the system of the two particles is isolated in the sense that they have no interaction with the medium. Suppose now that the two particles separate (the system decays, for example in **A** and **B**). **A** and **B** go away in opposite direction and can reach very large distances. Even if they are separated by large distances the two particles stay correlated (they are entangled).*
*If we measure the spin projection of particle **A** we can get $+\frac{1}{2}$ or $-\frac{1}{2}$ with a probability of 0.5. Suppose that in the measurement we find $+\frac{1}{2}$. By this measure we fix definitely the value of the spin projection of particle **B**. If we measure the spin projection of **B** we find inevitably $-\frac{1}{2}$. If, on the contrary the measurement on **A** had given $-\frac{1}{2}$ we would have found $+\frac{1}{2}$ for **B** since the spin of the total system is zero. This is true (and this theory of entanglement has been checked experimentally) even if the particle is far away. The information is in the system and has not to propagate over the space. It is instantaneous and does not depend on the speed of light. When such a correlation exists one says that the particles are entangled.*
Entanglement is a non-local property of quantum objects and has applications in quantum cryptography.

In a quantum computer, the data and the operations to be performed on the data are based on quantum properties such as superstition of states and entanglement just discussed in the box. So far experiments have been made to validate the concept on

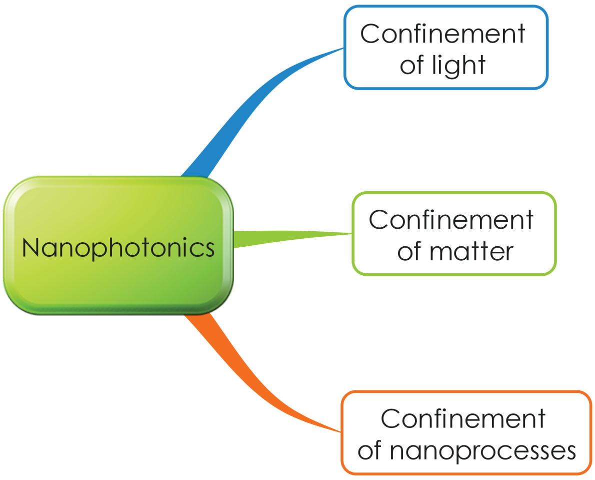

Figure 9.17: *Nanophotonics encompasses several nanoscale confinements indicated in the figure.*

simple operations and a small number of qubits. We are however far from big quantum computers which could solve problems much faster than classical computers.

Quantum cryptography encompasses cryptography but also the possibility to break cryptographic systems. It is an application of entanglement. It can provide unbreakable cryptosystems because it is impossible to measure a quantum system without disturbing it. Consequently if someone has interacted with your message, you know it for sure.

9.3 Nanophotonics

Nanophotonics deals with light-matter interactions occurring at the nanoscale. More precisely the US academy of sciences defines nanophotonics as "the science and engineering of light matter interactions that take place on wavelength and subwavelength scales where physical, chemical or structural nature of natural or artificial nanostructured matter controls the interactions".

9.3.1 Controlling light

The wavelength of visible light goes typically from about 380 nm to 780 nm, which is far above the nanoscale limit fixed around 100 nm. More precisely, nanophotonics is concerned when the interactions are controlled by the physical or chemical properties of nanostructures or by their structure.

Nanophotonics can be divided in three main broad areas depending on the nanoscale confinement which is involved. They are indicated in figure 9.17. There can be confinement of matter, light or nanoprocesses.

Finally, nanoscale optical memory or nanoscale conformation dynamics concerns are examples of applications of the nanoconfinement of photoprocesses. The aim of this area of nanophotonics is to control photoprocesses in nanodimensions.

These points are summarized in figure 9.18.

Waveguides allow confining and guiding waves such as electromagnetic waves and in particular visible light. Examples are shown in figure 9.19. Optical fibers are a common example of waveguides. The photons trapped inside the fiber cannot escape except at the

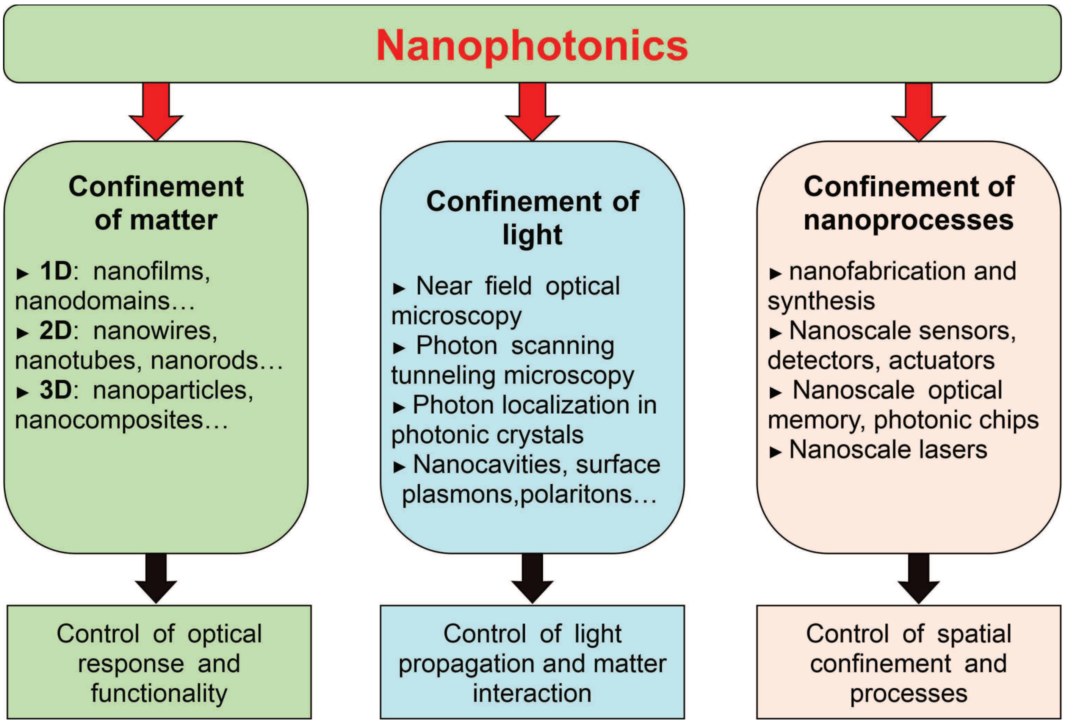

Figure 9.18: *Block diagram representing the main fields and applications in nanophotonics. Image courtesy of Paull Drude Institute, Berlin.*

ends of the optical fiber. A wave guide has generally a structure made of a material with a high index of refraction surrounded by a material with low index of refraction which constitutes the cladding. Waveguides are useful for optical interconnections. They could replace some of the metal interconnections but it should be kept in mind that even if light is faster to propagate in the material of a wave guide compared to electrons in a metallic wire, the distance over which light has to travel should not be too long otherwise electrons will be faster if the length of the interconnection is much shorter than that of the light interconnection.

A point concerns the conversion of an electronic signal to an optical signal and vice versa which introduces complications, extra-energy consumption and delay. A great interest of optical interconnection and treatment is that the energy dissipation of light is negligibly small compared to that of electrons (Joule effect).

Confinement of matter concerns nanoparticles or nanocomposites, for example. Here again it gives the ability to localize matter in nano-dimensions in order to control the optical behavior and functionality

Nanowires have a diameter in the nanometer range. Other Semiconducting nanowires can be made and used in the laboratory. They are usually synthesized by vapor-liquid-solid growth and can be doped to give p or n-nanowires. Nanowires of GaP, GaN, Si and InP have been made. Field effect transistors using nanowires have been realized. Si-nanowires are of special interest because they can be more easily used in the electronics silicon industry. An example of nanowires synthesized by vapor-liquid-solid deposition is shown in figure 9.20.

Nanoscale optical memory or nanoscale conformation dynamics are example of applications of the nanoconfinement of photoprocesses. The aim of this area of nanophotonics

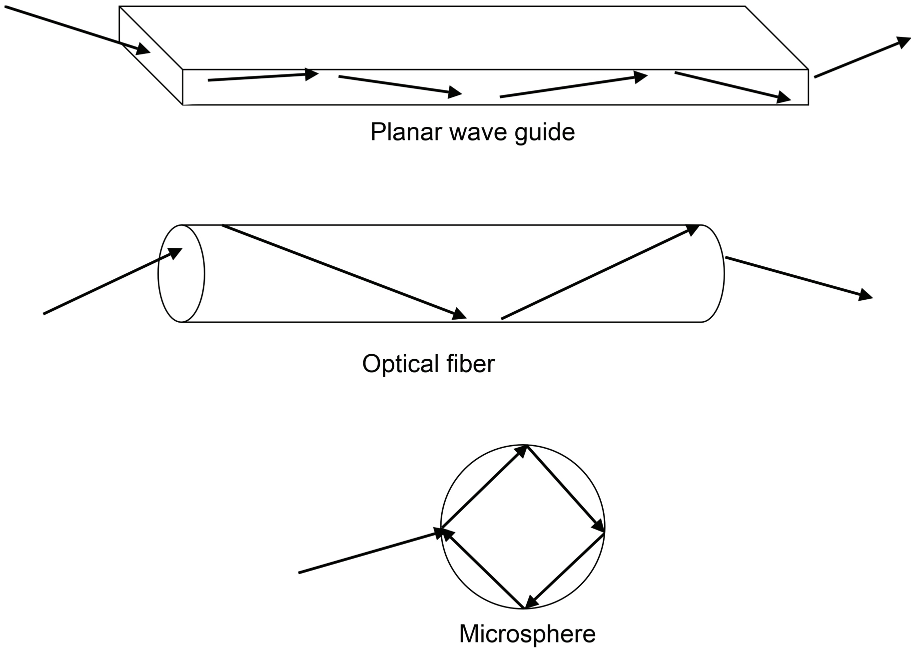

Figure 9.19: *Drawing of different light confinement which can be performed in nanophotonics. A planar waveguide corresponds to 1-D confinement, an optical fiber to a 2-D and a microsphere to a 3-D confinement. Inspired from A.Sharma, Nanophotonics, an overview, NSF-RISE Workshop (2007).*

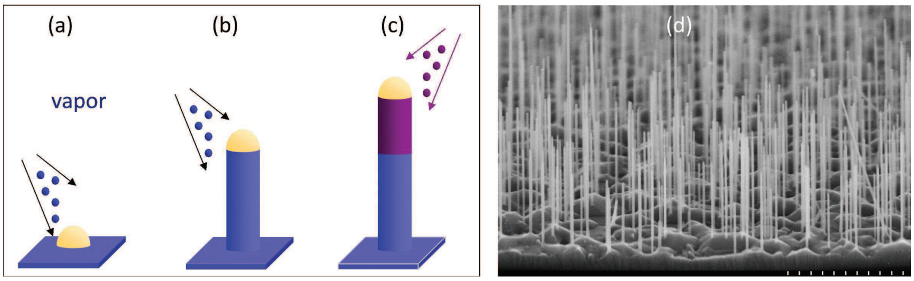

Figure 9.20: *Formation of semiconductor nanowires via vapor-liquid-solid growth mechanism, first introduced by Wagner and Ellis at Bell Labs in 1964. (a) Deposition of catalyst, eutectic formation with vapor. (b) Nucleation at catalyst/substrate interface, growth of nanowires. (c) Formation of axial nanowire heterostructures. (d) SEM image of GaAs nanowires on Si (Image from PDI) Scale bare: 1 μm.*

is to control photoprocesses in nanodimensions.

9.3.2 Photonic crystals

Photonic crystals belong to the nanophotonics domain but are treated separately due to their importance. The first studies on the subject go back to 1887 but a century was needed before substantial progress was made thanks to the advances in technology and characterization.

Photonic crystals are artificial periodic nanostructures with a period of the order of the optical wavelength. More precisely, the periodicity should be of the order of half the wavelength of the light to be diffracted. This means about 350 nm for red light and about 200 nm for blue light. Photonic crystals have some analogy in terms of structure to a solid state crystal (semiconductors or insulators). Because of its periodicity, a solid state crystal has a band gap (or an energy gap) which is a range of energy without electron states located in between the valence gap filled with electrons in the case of semiconductors or insulators and the conduction band which is empty.

Photonic crystals have bands of photons and a photonic band gap can be present. It is also possible, with a photonic crystal, to make a localization of light. A photonic crystal is characterized by its dimensionality. It can be 1-D, 2-D or 3-D.

The photonic bandgap corresponds to energies for photons which are forbidden. It means that photons with incident energy in this gap cannot enter the crystal. On the other hand, electrons cannot emit light in this gap. A photonic crystal acts an optical insulator for certain values of the wavelength. In the same way as an electrical insulator prevents electrons to travel through, optical insulators prevent light to go through.

Semiconductor can be doped. It is possible to do so in the case of photonic crystals. Impurities (atoms or defects) are introduced in the gap to control light propagation and radiation.

From electrons to photons

In optics the goal is to completely control light propagation at any scale and find materials to do it.
Semiconducting materials based on crystal lattices can do that for electrons. A crystal is a periodic arrangement of atoms or molecules. Diamond, for example, is a crystal. A crystal lattice behaves like a periodic potential whose properties depend upon the geometry of the lattice and which can be modified by adding dopants in the crystal. Electrons can behave, under certain circumstances fulfilled inside the crystal, as waves and new properties compared to a classical behavior of electrons happen. For example electron waves meeting certain criteria can propagate without scattering from the constituents of the crystal. There are situations in semiconductor crystals like silicon or germanium, or insulators like diamond, where electrons are forbidden to propagate with certain energies. This is because there is a gap in the energy band structure of the crystal separating the valence band from the conduction band.
The photonic crystal is the optical analogue of the semiconductor or insulator crystal. However, instead of having atoms or molecules at the sites of the crystal, there are pieces of material with different dielectric constant. As a consequence, the periodic potential existing in semiconductor crystals is replaced by a periodic dielectric function, i.e. a periodic index of refraction. By choosing properly the dielectric material and its arrangement, it is possible to make photonic band gaps. In such a case, light with a certain wavelength cannot propagate in certain directions.
If, in some range of wavelengths, a photonic crystal prevents the propagation of light in any direction and any polarization of light, the photonic crystal is said to have a complete photonic band gap. 3-D photonic crystals, where the dielectric lattice is periodic along the three axes have this property.
Photonic crystals also allow controlling light in a similar way as metallic waveguides and cavities are used to control microwave propagation. With 1-D photonic crystal, for example, it is possible to reflect light incident from any angle and any polarization.
A 1-D photonic crystal is periodic in one direction. In a 2-D photonic crystal the periodicity is along two directions and a 3-D photonic crystal is periodic along three directions. There are photonic crystals in nature for example in the wing of the morpho rethenor butterfly or in a peacock feather. This structure gives them beautiful colors because of their specific optical properties.

Photonic crystal and complete photonic band gap systems can be engineered on demand. Several parameters can control that. They are indicated in figure 9.21. One can play on the periodicity of the refractive index to design photonic crystals of different dimensionalities (1-D, 2-D or 3-D). The type of crystal lattice (body centered cubic, sim-

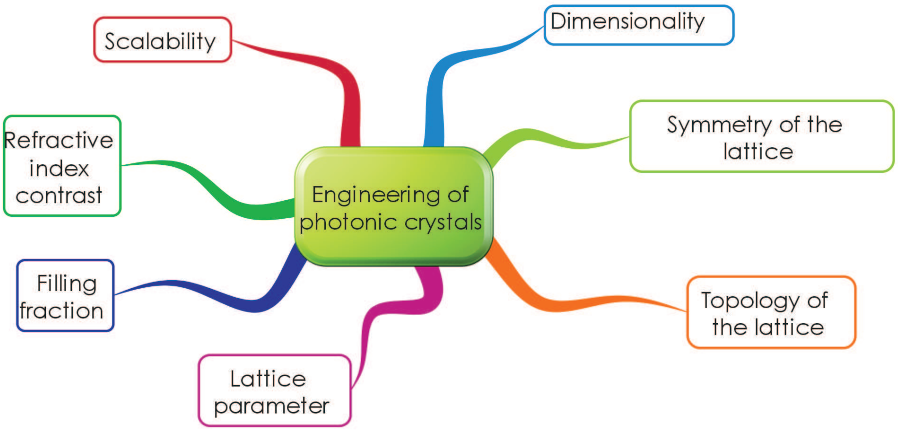

Figure 9.21: *It is possible to play on several parameters to make photonic crystals with required properties.*

ple cubic, face centered cubic, simple hexagonal or body centered cubic) determines the symmetry of the lattice. A variation of the topology affects the photonic band structure. The lattice parameter is the distance separating the building blocks of the lattice. This distance determines the range of wavelength where the photonic crystal will work. The filling fraction of the lattice, which is the relative amount of refractive material in the lattice, has also an influence on the photonic band gap. The refractive index contrast is the ratio between the high dielectric constant of the material located at the site and the low dielectric constant of the rest. This parameter has an influence on the scattering process of light. The scalability allows, by changing some of the length parameters, to have similar properties at different wavelength.

The domain of application of photonic crystals is very rich and we shall just quote here a few of them.

Photonic crystals without complete photonic band gap can be used as supercollimators or superlenses. The negative index of refraction which can be obtained can be used for these applications. In the same spirit, a super prism effect is obtained with two different photons arriving at the same angle of the crystal but with a slightly different energy. This could have applications in integrated multiplexers.

There is an interest to develop complete integrated circuits where photons carry information instead of electrons. This comprises in particular waveguides based on 2-D photonic crystals. As an illustration, figure 9.22 shows two examples of wave guide which can be obtained.

Optical fibers based on photonic crystal can already be found commercially. Bragg gratings are an example of a 1-D photonic crystal which can be used to measure concrete constraints in dams, for example. A 3-D photonic crystal can be either isotropic or anisotropic. Anisotropy is useful to design an optical switch.

Confinement of light includes, for example, near field and far field optical microscopies. It comprises also second–harmonic generation microcopies, nanocavities (as shown at the bottom in figure 9.23). Basically the aim is to be able to localize light in systems of nano-dimensions and control its propagation and interaction with matter.

Photonic crystals have also applications in the microwave domain. They help to optimize the performance and directionality of microwave antennas.

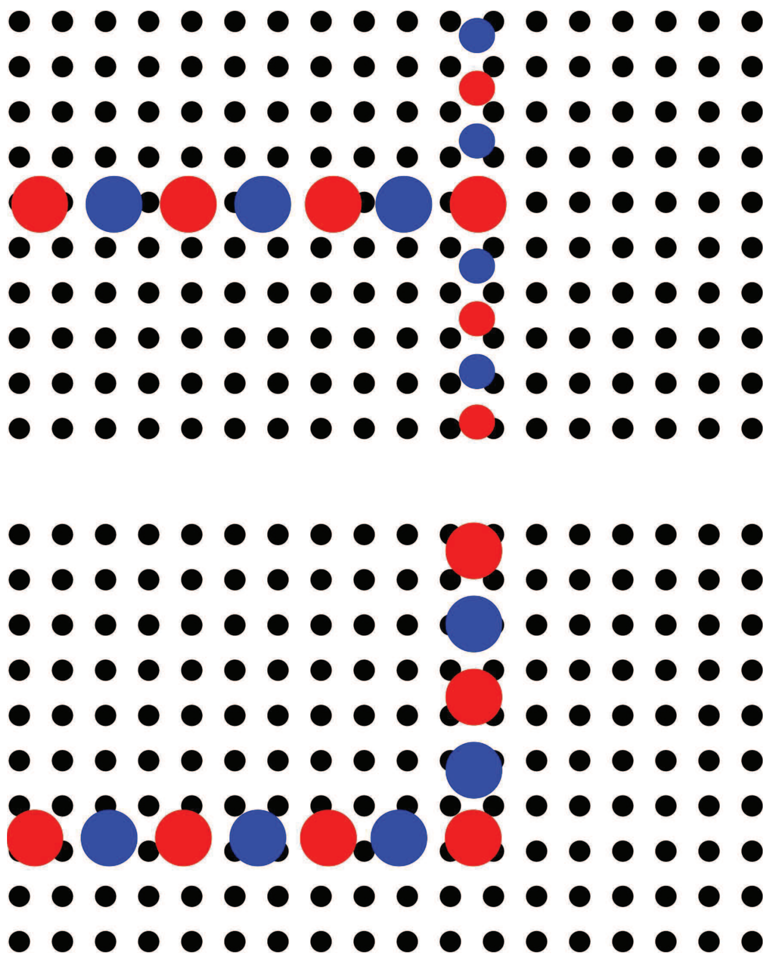

Figure 9.22: *Two schematic examples of waveguides using photonic crystals. On top a wide-angle splitter is shown and at the bottom a lossless sharp bend wave guide. The lattice is represented by the small black dots which correspond to high dielectric material. The light wave is represented by alternating blue and red dots.*

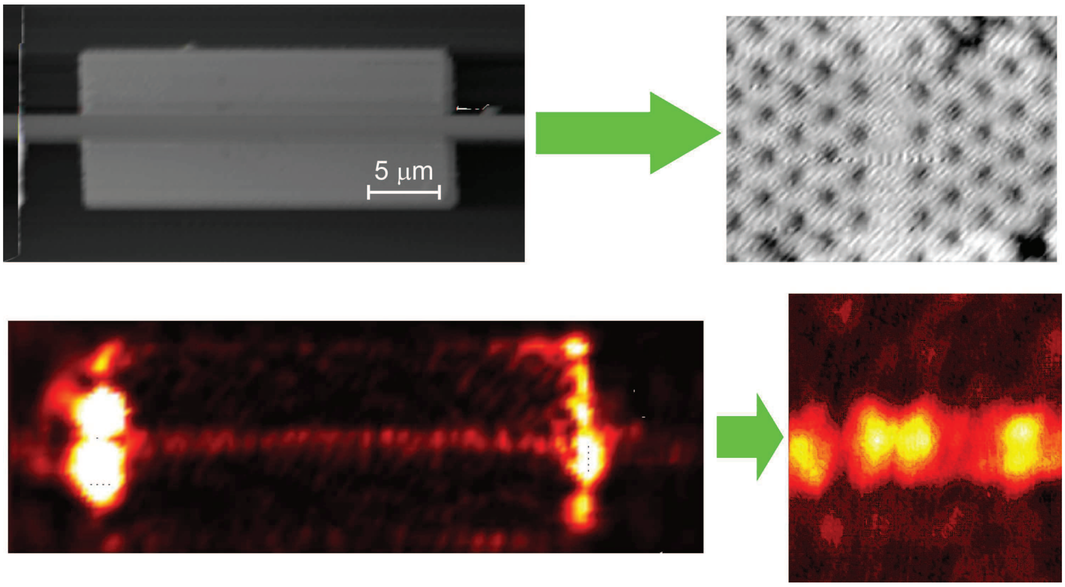

Figure 9.23: *Local probe view (known also as a near-field image) of the optical wave propagating in a photonic crystal waveguide. The image on top is a topographic view of the guide while the image at the bottom is a near-field image. Courtesy of CEA. Clefs CEA n°52.*

It is also possible to make microcavities where it is possible to trap light for a long time. Putting defects in crystals trap resonant modes. It is possible to get tunable cavity modes.

9.3.3 Plasmonics

Metallic structures provide an efficient way to manipulate light at length scales smaller than the wavelength of the photons involved. This is so because at the interface between a dielectric (such as silica glass) and a metal (such as silver or gold) a surface plasmon oscillation can be generated. A surface Plasmon is a coherent (collective) electron oscillation (and they are plenty of electrons at the metal surface) propagating along the interface together with the electromagnetic wave associated with light. Plasmons are the quasiparticles associated to a Plasmon oscillation in the same way as photons are the particles associated to an electromagnetic wave. The nice thing is that the wavelength of surface plasmons is much smaller (of the order of ten times less) than the wavelength of photons. For example, using a He-Ne laser to excite a silica-silver interface with a wavelength of light at 633 nm excites a surface plasmon oscillation at 70 nm. Tuning the laser wavelength around the Plasmon resonance decreases the surface plasmon wavelength down to the nanometer range. This gives the possibility to make plasmonic nanocircuits to treat light at dimensions smaller than the wavelength.

It is possible to put a light source, such as a quantum dot, close to the metal and excite surface Plasmon oscillations. If it is a light emitting diode (LED) put in the plasmonic structure, it is possible to electrically excite surface plasmon oscillations. Conversely, it is possible to enhance LED emission by surface plasmon waves.

Arrays of metal nanoparticles can be used as optical waveguides because plasmon waves can linearly propagate along nanoparticles chains.

Figure 9.24: *Possible applications of metamaterials.*

9.3.4 Metamaterials

Metamaterials are artificial materials which are engineered composites. This gives them physical properties different from what can be found in nature. They are made from conventional elements such as metals, plastics, ceramics, *etc.* engineered in such a way that they exhibit new properties due to the arrangement of the individual elements rather than due to the properties of the individual elements only. In other words the behavior of metamaterials is determined by the sum of the elements rather than by the elements themselves.

Photonic crystals have a lattice size of the order of the wavelength of light in order to have a photonic band gap. Metamaterials have a lattice constant much smaller than the wavelength because the diffraction phenomenon is avoided contrarily to photonic crystals where it is required to build a photonic band gap. Some metamaterials can have a negative refractive index.

A fascinating application of plasmonic metamaterials is trying to make an invisible cloak. To be invisible one needs at least that the refractive index of the invisible body is equal to the refractive index of air. This can be achieved in some range of frequencies using plasmonic metamaterials.

Metamaterials have many possible applications as shown in figure 9.24.

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