NANOYOU Teachers Training Kit in Nanotechnologies

Chapter 4 – Information and Communication Technologies (ICT)

MODULE 2- Applications of Nanotechnologies

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Chapter 4: Applications of Nanotechnologies- Information and Communication Technologies (ICT)

Nanotechnology in many respects **is already a key player in ICT** research and development, in both academia and industry. Computer microprocessors and memory storage devices have followed a path of miniaturisation in the last 20 years that has "naturally" brought transistors to have dimensions lower than 100nm. There are now challenges to meet in continuing this miniaturisation path because as the materials of semiconductors, metals and insulators are reduced to nano-size, quantum effects start to predominate and to determine their properties. This is resulting in a number of issues. Nanotechnology offers the opportunity to exploit, rather than avoid, quantum effects for the development of the next generation of integrated circuits. As miniaturisation cannot proceed forever with the methods and tools that have been used so far, new approaches will be needed. Nanomaterials, precisely for their quantum properties, and nanotechnology tools allow the creating of new data storage and processing methods. These developments are discussed in the section "Integrated circuits" and "Data storage". The section "Photonics" looks in details at this emerging technology for opto-communication. Another essential contribution of nanotechnology is in the field of displays, which are becoming thinner, lighter and less energy-consuming. The contribution of nanotechnology in this area is covered in the section "Displays".

But the evolution of the ICT sector will most likely go beyond what we consider today as "electronics" (i.e. devices that perform a task for us). There are visions of having electronics embedded in our clothing, in the environment around us in what is conceived as a network of devices that create "ambient intelligence". Although still more a vision than reality, there is intense research on the realisation of the tools required to realise "ambient intelligence".

This chapter looks at these various applications areas in the ICT sector and considers what the impact of nanotechnologies can be in each.

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Integrated circuits

In the late 1960s Gordon Moore, co-founder of Intel, made a memorable observation that later became known as "Moore's Law". He observed that the number of transistors on a chip roughly doubled every eighteen months. Originally this was only an observation but was later adopted as an industry goal. The progression in transistor density on a chip in the last 40 years has indeed followed Moore's law (**Figure 1**). In order to keep up with this law, transistors have become smaller and smaller. The first transistor was about 1 cm high and made of two gold wires 0.02 inches apart on a germanium crystal. The latest transistors from Intel (Penryn and Nehalem) have 45 nm feature sizes and in a quad-core configuration have over 731 million transistors! These numbers give an idea of the enormous miniaturisation efforts that has been achieved by the semiconductor industry.

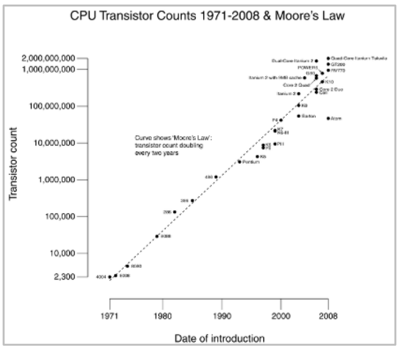

Figure 1. Curve shows the increase in number of transistors on computer chip, which follows Moore´s prediction of doubling every 18 months. (Image credit: http://commons.wikimedia.org/wiki/User:Wgsimon, Creative Commons Attribution ShareAlike 3.0)

Scaling down of transistors has been the driving force for a number of reasons. Transistors are the basic building blocks of the elements in an integrated circuit (microprocessor, mass memory, logic gates, etc). Integrated circuits are the core of the information and memory storage device that are an essential part of all electronics we use: from computers, to refrigerators, to cars, mobile phones, etc. As the size of the transistor is reduced, its density on a chip increase, which increases the speed, the amount of memory stored per area and the number of functions that can be integrated on a single device.

TIP FOR TEACHER: To illustrate this, ask students to describe the size and function of the first mobile phone they can remember. In the early 1990s it was just a phone, quite bulky and heavy. Later it became smaller, lighter, and with many more functions. Nowadays we have all-in-one devices that are phones, digital music players, radios, video cameras, internet platforms, and more!

The enormous advances in computing that have characterised the last fifteen years (including the advent of the internet and the "Information Age") has been enabled by the miniaturisation of all elements in computer chips. In the future, high performance computing is expected to deliver tools that we don't yet have, like a real-time language translator or ubiquitous sensing.

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Scaling down transistors cannot go on indefinitely with the tools and materials we now have. Experts say that Moore's law will last until the year 2015, perhaps a few years beyond. Eventually, we will reach a point where the transistor is so small that quantum effects start to predominate. In a transistor the "on" and "off" state are determined by the flow (or not) of electrons through the n-p junction (gate). At very low dimensions (e.g. 1 nm) electrons will be able to pass through the gate via tunnelling, which is a fundamental quantum effect (for details see **Chapter 4 in Module 1 "Fundamental nano-effects"**).

Another issue is **power consumption** and **heat generation**. This is an issue that everyone using a modern mobile phone experiences daily. As the amount of functions integrated on a mobile phone has been increased, so it has the amount of power consumed (the type and battery lifetime has become determinant on the quality and performance of the device and its cost). This leads also to heat generation, which at smaller scales becomes even more important and is considered a research priority. Reducing power consumption is also critical, not just for the performance of the device but also for environmental considerations (energy saving).

In simple words, by continuing to use the current technology, we will reach a stage of development where further scaling will create opposite effects such as growing energy consumption in standby-mode, and performance restrictions in active mode. New technologies will be needed to allow miniaturisation of electronic devices along Moore's curve.

WHAT CAN NANOTECHNOLOGIES DO? Current transistors are already below 100nm, so technically the semiconductor industry already makes use of nanotechnologies. Continued miniaturisation of transistors using the CMOS platform (denominated "More Moore technology") has already produced transistors smaller than 100nm. This threshold was crossed around the year 2000, and today transistors are 45 nm. Although the **"More Moore"** approach does involve working with materials with nano-scale sizes (and related fabrication methods), it has the task of scaling existing CMOS processes and reaching the "CMOS limit" (meaning the size limit obtainable with this technology). Some consider this not to be "true nanotechnology", since it does not make explicit use of the unique properties of nanomaterials (quantum effects, etc.). This development line, meaning developing fundamentally new approaches to information processing and data storage, beyond what we use today such as self-assembly, or totally new materials (such as molecular electronics) belongs to the domain called **"Beyond CMOS"**. In addition to these two domains is the **"More than Moore"** domain, meaning technologies that provide functionality beyond traditional computing (such as intelligent systems that can interface with the user

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and the environment). Without going too much into the technical details we will outline in the next sections the impact of nanotechnologies in these **domains of technology innovation**.

"More Moore"

Semiconductor components (microprocessors, mass memories, logic gates) will need to follow the miniaturisation trend described by Moore's law to keep up with the industry demand ("More Moore"). This means introducing new materials and new device architectures. One of the most critical elements in current transistors is the **insulating layer** between the two gate electrodes. This layer is now made of silicon oxide; as the transistor is made smaller, the thickness of this layer is reduced to a point where leakage (passage of electrons between the two electrodes when voltage is off, i.e. tunnel leakage current) becomes a problem. In the latest processors silicon dioxide is replaced with a **high-permittivity material ("high-k")** for low power consumption. Hafnium compounds are the most promising high-k materials and are currently used in Intel 45-nm technology generation (node).

As the materials used in transistors change and smaller features are needed, the **fabrication methods** used in CMOS also need to evolve. In general, the limit of the smallest size that can be created depends on the tool used. Features about 500 nm in size could be fabricated through optical lithography, but in order to create smaller features extreme-UV lithography was needed. Advances in CMOS technology have always implied enormous investments for the development of fabrication techniques able to deliver the required transistor size. As new materials are introduced into CMOS technology, new fabrication technologies also need to be integrated. For instance the 45 nm node is created using a fabrication process different from the conventional top-down lithography approach. Hafnium materials are normally deposited using the **Atomic Layer Deposition** method (ALD) which is a bottom-up fabrication method (for a review of fabrication methods used in nanotechnologies see **Chapter 7 in Module 1 "Fabrication methods")**. The method is believed to be used in the latest generation of Intel processors. Another nano-fabrication method that is being considered to continue Moore's law of miniaturisation is **Nano Imprint Lithography**. Although there are numerous fabrication techniques that can be used to make nano-scale features (of which the Scanning Tunnelling Microscope is the most powerful in terms of capabilities), in the context of the semiconductor industry only a few are feasible candidates. Any new fabrication technique (different from conventional lithography) must satisfy a number of stringent requirements: resolution, defect rate, throughput (meaning being capable of producing many features quickly), and must be easily integrated into current fabrication facilities (otherwise a massive investment of money would be needed). Nano imprint lithography seems to be the

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technology that at the moment can best satisfy those needs and will most likely be the technology used for the future 32 nm and 22 nm nodes.

Another key element in integrated circuits which is starting to create problems is the copper **connectors between the transistors**. The effective resistivity of copper increases at smaller dimensions and the integrity of the signal as it travels along the connector is becoming a major issue. **Nanotubes and nanowires** are now being considered as alternatives to conventional copper. Carbon nanotubes are considered an ideal material since they can be outstanding conductors (with almost zero resistance and heat dissipation), they are extremely strong mechanically and inert to chemicals. The current problem is fabrication (pure carbon nanotubes are hard to produce) and alignment.

More-than-Moore

The "More than Moore" domain refers to the development of functional components beyond the traditional computing ones (microprocessors and memory). The **future electronics will integrate an interface with the real word** (so called "ambient intelligence") and will need to integrate not just a processor and memory, but also sensors, actuators, RF interfaces, etc. They will also need to satisfy a number of requirements, such as low power consumption, flexibility, thermal management, and last but not least, cost. Nanotechnologies are going to have an essential role in all those systems. In the last part of this chapter we provide some ideas of what "ambient intelligence" might do for us and what it might imply in terms of social and ethical consequences.

A detailed analysis of the technical elements that will be integrated in these systems is not covered here as it would be too advanced for secondary-school level. We will only outline that new materials and fabrication methods will be needed in order to integrate these smart multifunctional systems and connect them with the outside word. Different nanodevices based on different technologies and processes will need to coexist within the same package. This is conceptually very different from the current concept of "multi-functionality" where different "packages" with specific functionalities are separated and added together only the end of the manufacturing process. In the future there will be "system in package" solution where the different functionalities are integrated in one 3D architecture as the package is constructed (nano-sensors, nano-actuators, processors, etc). This requires the **heterogeneous integration of electrical and non-electric components**, which in turn requires new materials to be developed (like plastic electronics). In the short term nanotechnologies will probably contribute in improving the properties of current materials, for instance with the addition of nanoparticles to adjust parameters such as electrical resistance, thermal conductivity, coefficient of

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thermal expansion, etc. In the long term nanotechnologies are expected to be used to develop nanoscale interconnectors and self-assembly technologies to go beyond current architectures.

Beyond CMOS

It was mentioned before that miniaturisation of microprocessors and memory cells cannot continue indefinitely, and Moore's law will necessarily come to a halt, if the same CMOS technology is used. On the other hand, miniaturisation and system integration will surely continue to be fundamental in our communication society, even more than today. Ubiquitous sensing, ambient sensing, "constant" networking and communication in an "always connected" state will most likely be part of our future. For this to be possible, new materials and processing methods will be required once the dimensions of transistors become so small that quantum effects start to predominate. Nanotechnologies will allow us to exploit these effects and realise the future generation of electronics to store and process information where quantum effects and other nano-effects determine the property and functionality of the device. Without going into too much detail, below we describe some fundamental developments that researchers are working on to ensure that miniaturisation can continue beyond the intrinsic limits of the CMOS technology.

New data storage and processing nanotechnologies

Microprocessors work by processing information through passage of an electrical signal. In the future information processing will be done using a state variable different from electric charge, such as spin (spintronics), molecular states (molecular electronics), photons (photonics), mechanical state, resistance, quantum state (including phase) and magnetic flux. These new state variables will require new materials to be used (e.g. relying on spin implies using magnetic materials rather than a semiconductor) and new functional organisation of the device (architecture).

Below is a list of some new concepts that are being developed for processing and data storage that make use of state variables different from the "conventional" ones used in CMOS (electric charge).

- **Spintronics**: this is a new type of technology that makes exploits the spin of the electron (rather than only its charge) to store and process information. It requires thin layers of magnetic materials. The **giant magnetoresistance effect (GMR)** represents the first type of this new technology, and is used in the new generation memory devices like the Magnetic Random Access Memory, or **MRAM** (used for instance in the Apple iPod). The GMR and data magnetic storage devices based on this effect are discussed in the next section, "Data Storage".

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- **Photonics**: Another possibility is the use of photons (rather than electrons) in the visible or IR range to transmit and process data (**optical communication**). In this case semiconductors (like silicon) can no longer be used since they cannot emit and transport light efficiently. Other materials (photonic crystals) engineered at the nanoscale need to be used. Photonic crystals and their use in optical communication are discussed in the dedicated section "Photonics" of this chapter.

- **"Quantum electronics"**: this term means the explicit use of the **tunnelling effect** to transport electrons from the source to the drain of the transistor. One such transistor exists and is called the **single-electron transistor (SET)**. In this type of transistor, between the source and the drain is a quantum dot: electrons must tunnel through this dot in order to get from the source to the drain. Basically this is like having two electrodes (source and drain) separated by a thin insulating barrier with a third electrode (the quantum dot, or **quantum island**) in the middle of this insulating gap. The transport of charge from the source to the quantum island and then from the quantum island to the drain occurs via the quantum mechanical process of tunnelling.

- **Carbon nanotube transistors**: In many ways carbon nanotubes are considered a "dream" material when it comes to electronics: they can be conductive or insulating depending on their chirality (and when they are conductive, they are extremely good electronic conductors, with little resistance and consequently little heat dissipation); they are strong (mechanically) and chemically inert, they are resistant to high temperatures, and they can be functionalised with specific molecules to act as anchoring points. Carbon nanotubes are about 1-2 nm in width, they are as narrow as the double stranded DNA molecule (the molecule that carries our genetic information). So arranging nanotubes into electronic circuitry could allow miniaturisation by a factor of about 100 over the current limit.

- **Molecular electronics**: molecules in natural systems (plants, animals) are arranged in macromolecular systems (nanostructures) that perform numerous tasks which involve the transmission of charges, photons, etc. These macromolecular systems have developed though million years of evolution and are an example of excellence when it comes to efficiency of work! One example is the electric flow in nervous signalling, or the control of charges in the ionic pump, or the absorption of light and transmission of photons and charge in plant chlorophyll. The examples are numerous. Molecular electronics is a branch of nanoscience that aims to make explicit use of molecular assemblies for the transmission and storage of data. The field includes molecular wires, molecular switchers, molecular sensors and other "hardware" components of electronics. The idea is to assemble molecules in nanostructures that can perform a specific function (such as transport of charge) depending on its

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configuration. An example can be a two-terminal transistor having three benzene rings that act as the charge transfer site. The central benzene ring is functionalised with two groups (NH_2 and NO_2) that make the overall molecule very susceptible to an electronic field. The electric field can induce the distortion (twisting) of the molecule. Basically this gives rise to an electronic device where if a voltage is applied, the molecule twists in such a way that the current flow is stopped; when the voltage is turned off the molecule springs back to its native conformation and current flows again. This is just one of many molecular electronic devices under research. In order to fabricate and test such small devices, nano-tools like the STM are needed. These types of devices are still in a very early stage of development because of the time required to fabricate and test them. Also, in order to make any useful molecular circuit a vast number of devices need to be orderly arranged and securely fixed to a solid support to prevent them from interacting randomly with one another. In the future molecular wires (for instance made of conductive polymers such as polypyrrole) or carbon nanotubes could be incorporated into integrated circuits, which would notably reduce the size of computer chips (wires used today use about 70% of the real space on a chip!).

Data storage

Data storage is a key component of many devices that we use every day: computers (which contain both a hard drive and RAM), mobile devices (in which the memory medium is normally a memory card, think of your digital camera), and portable media players (like iPods, mobile phones, etc. that use Flash memory).

Data storage technologies include two main groups, **hard disk drives** (having a mechanical component) **and solid-state data storage devices**, which can be further divided in volatile and non-volatile. Volatile means that memory is lost once the power is turned off; non-volatile means that memory is retained when the power of the device is switched off.

- Volatile memory storage devices today include mainly **Static Random Access Memory (SRAM)** and **Dynamic Random Access Memory (DRAM)**.

- Non-volatile memory storage devices, like **Flash memory**, are used in mobile devices and portable media players.

Each type of memory has its advantages and disadvantages: DRAM has a smaller memory cell size than SRAM, therefore can store more data but requires to be refreshed periodically, consuming power and

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lowering speed; SRAM can store less data but is faster; flash memory is non-volatile, making it ideal for devices where power is often turned off.

Memory storage devices are described by their capacity (amount of data in MB), memory density (a function of the capacity and the size of the memory cell), lifetime (how many read/write cycles it can last before it degrades), read/write speed and cost.

The concept of a universal memory

The need for memory storage devices with an ever-increasing density capacity has been the driving force for this industry. The motivation has been the need to keep pace with Moore's law (and therefore reduce the size of the memory devices), and the proliferation of mobile devices which demand low power operation and batteries that have a low consumption in standby mode. These two trends have catalysed the search for a universal memory, meaning a memory storage device that addresses the major technical challenges of existing memory technology (DRAM, Flash memory, etc.), while combining the value propositions of each – speed, density and non-volatility. Although a universal memory is still a concept, research for its realisation is intense and new technologies that have been developed are trying to go in this direction. Nanotechnology is an essential part of all of these.

Nanotechnology developments in data storage

In the last few decades the dimension of memory storage cells has been decreasing, following Moore's law. This continuing size-reduction has however led to memory cells with extremely small transistors. At the current 90nm process node, SRAM and DRAM are beginning to suffer from a number of scaling issues. As the semiconductor is reduced in size, quantum effects come into play, and electrons can "jump" from the source to the drain by tunnelling or just by thermal motion. Also, other elements become critical, like charge leakage due to silicon substrate crystalline defects. In Flash memory an insulating layer of silicon oxide "wraps" the gate architecture and serves as a barrier for storing the change. As this layer becomes thinner, the charge can start to leak out of the device. These are only a few of the problems facing memory storage development today.

To deal with these challenges, new concepts that make use of fundamental nano-concepts and nanotechnology tools have recently been introduced:

- **Magnetoresistive Random Access Memory (MRAM)**, where each memory cell is made of two ferromagnetic thin layers separated by an insulating layer.

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- **Ferroelectric RAM (FeRAM)**, similar in architecture to MRAM, but where a ferroelectric layer replaces the dielectric layer

- **Resistive RAM (RRAM)**, in which a conduction path is created through a dielectric material

- **Phase transition memory**, also known as **phase change memory (PCM)**, which uses the phase transition of a material from crystalline to amorphous.

- **Nanotube RAM**, a trademark of the company Nantero (NRAM^{TM}), which uses carbon nanotubes to determine memory states.

Each of these technologies has a different level of maturity and time will be needed before they can compete with Flash memory. However, development in this sector is very rapid and is projected that by 2012 nanotechnology-enabled storage devices will account for 40% of the total memory market.

MRAM

Magnetic materials are used in **Magnetoresistive Random Access Memory (MRAM)**, in which each memory cell consists of two magnetic thin film materials separated by an isolating layer.

Magnetic multilayer nanocomposites (meaning very thin film made of magnetic materials) display **magnetoresistance** properties. Magnetoresistance is a phenomenon where the application of a DC magnetic field changes the resistance of a material. In metals this effect occurs only at very high magnetic fields and low temperatures. In 1988 it was discovered that a very pronounced effect, now known as the **giant magnetoresistance effect (GMR)**, could be obtained in materials made of alternating layers of nanometre thickness of ferromagnetic material and non-magnetic but conducting material (**Figure 2**). The magnetic layers forming the multilayer can have their magnetisation vector aligned (parallel) or not (anti-parallel), as in **Figure 2.** Polarity is persistent, therefore the device is **non-volatile**. If current flows through the device and the layers have a parallel configuration, the resistance is lower than if they were to be anti-parallel. In the MRAM memory cell, the two thin layers of metals are separated by a thin insulating material. This gives rise to another effect called the **tunnelling magneto resistance (TMR) effect**. In contrast to GMR, TMR uses ultra-thin non-conducting spacer layers, which renders the ferromagnetic layers electrically

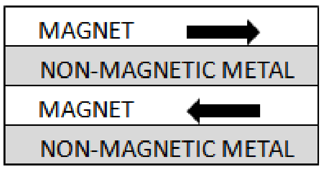

Figure 2. Arrangement for producing giant Magnetoresistance: layers of nonmagnetic (but conductive) material alternating with oppositely magnetised (arrows) ferromagnetic layers.

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isolated. Electrons can thus tunnel through this barrier.[1] As in the GMR effect, the passage of a current changes the polarity of the magnetic material causing either a high or a low resistance across the insulating barrier, which can be read as a 1 or a 0. To write data in such memory cells, a current is passed through the cell, which alters the polarity of the magnetic layers.

Some materials have been discovered having even larger magnetoresistive effects than layered materials and this phenomenon is called **colossal magnetoresistance (CMR)**. These materials (e.g. LaSr- and LaCa-manganites) have a peculiar crystal structure that is responsible for the CMR effect and could have a number of applications in memory storage devices.

NRAM™

The company Nantero, Inc. has introduced a new type of non-volatile random access memory called NRAM™ where the "N" stands for "nanotube" since it uses carbon nanotubes. The nanotubes are assembled as fibres and are suspended perpendicularly across trenches of etched silicon wafers. At the end of the silicon trench is placed a contact electrode. When a potential is applied between the fabric and the electrode, the fabric bends and touches the electrodes. The interaction is based on Van der Waals forces and remains also after the power is turned off. When the fibre is far away from the electrode, the junction has a high resistance and this is read as a "0" state. As current is passed, and the fibre touches the electrode, the junction resistance is lowered, and this is read as a "1" state. Carbon nanotubes are produced used a method alternative to the conventional one (chemical vapour deposition, CVD) and which does not require high temperatures. The process developed by Nantero, Inc. allows production of pure carbon nanotubes at room temperature. This is an added advantage to the technology as CVD requires temperatures so high as to damage the other constituents of the memory device. The NRAM™ is considered a very important development towards the concept of universal memory, and it has the advantage that it is fabricated using current CMOS technology platforms: this ensures immediate manufacturability.

Phase change memory

Phase change memory (**PCM**) (also named phase random access memory, **PRAM**) is another new and promising concept in **non-volatile memory storage**. It uses a material (chalcogenide glass) which can be

[1] *The tunnelling effect is a quantum mechanical effect which occurs when a small particle penetrates a barrier by using a classically forbidden energy state. This effect is based on the fact that particles, e.g. electrons, should be treated more as a wave then a hard sphere. Thanks to the tunnelling effect, an electric current will flow through a thin isolating barrier when a voltage is applied.*

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"switched" between two states, crystalline and amorphous, through the application of heat. The amorphous state has high resistance and is used to represent 0, whilst the crystalline state has lower resistance and is associated with the state 1.

Overall, PRAM (or PCB) is considered the most promising advancement in non-volatile memory solutions. In February 2008 Nymonyx started shipping the first PCM prototypes for customer evaluation. The product is named Alverstone; it is a 128MB PRAM, produced on a 90nm CMOS fabric. Nymonyx is the new STMicroelectronics and Intel non-volatile memory company. Advance in this technology is proceeding fast, and on December 2009 Nymonyx announced a paper showing the scaling of PCM to the 45nm lithography node for the first time on a 1 GB product with an effective cell size of 0.015μm^2. Nymonyx researchers report good electrical properties and reliability results, confirming that PCM has reached the maturity to become a mainstream technology for high density non-volatile memory applications.

Photonics

Photonics is the study of the interaction of light with matter. The field was opened up in the 1960s with the invention of the laser. Ten years later, the invention of the optical fibre as a means of transmitting information via light formed the basis for **optical communication**. The field is now enormous and consists of many sub-disciplines and applications, like laser technology, biological and chemical sensing, display technology, optical computing, fibre optics, photonic crystals and more.

In 1987 Eli Yablonovitch at Bell Communications Research Centre created an array of 1 mm holes in a material with a refractive index of 3.6. It was found that the array prevented microwave radiation from propagating in any direction. This discovery started the research on photonic crystals, but it took more than a decade to fabricate photonic crystals that do the same in the near-IR and visible range. Nowadays photonics crystals are an important nanomaterial investigated with numerous applications and in particular for optical communication.

Photonic crystals

A photonic crystal consists of a periodic structure made of dielectric materials that affects the propagation of light. Essentially, photonic crystals contain **regularly repeating internal regions of high and low dielectric constant**. Photons (behaving as waves) propagate through this structure – or not – depending on their wavelength. The periodicity of the photonic crystal structure has to be of the same

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length-scale as half the wavelength of the electromagnetic waves, i.e. ~200 nm (blue) to 350 nm (red) for photonic crystals operating in the visible part of the spectrum. Such crystals have to be artificially fabricated by methods such as electron-beam lithography and X-ray lithography.

Photonic crystals exist in Nature. For instance, in **Chapter 2 of Module 1 (" Natural nanomaterials")** it was shown how the beautiful blue wings of some butterflies owe their colour to their internal nanostructure, which is in fact a photonic crystal structure. Another example is opals.

Application in communication

Photonic crystals are now receiving much attention because of their potentials in particular in the **optical-communication industry**. The current explosion in information technology has been enabled by semiconductor technology and the ability to fabricate materials where the flow of electrons can be controlled in the most intricate ways. Photonic crystals promise to give us similar control over photons – with even greater flexibility because scientists have far more control over the properties of photonic crystals than they do over the electronic properties of semiconductors. The goal of putting more transistors on a chip (to make smaller and faster integrated electronic circuits) requires further miniaturisation. This unfortunately leads to higher resistance and more energy dissipation, putting a limit on Moore's law. Researchers are considering using **light and photonic crystals** (in alternative to electrons travelling in wires) for the new generation of integrated circuits. Light can travel much faster in a dielectric medium than an electron in a wire, and it can carry a larger amount of information per second. Given the impact that semiconductor materials have had on every sector of society, photonic crystals could play an even greater role in the 21st century.

Properties of photonic crystals

Photonic crystals are designed to confine, manipulate and control the propagation of photons in three dimensions. The properties of a photonic crystal are determined by the radius of the holes (or other features like dielectric rods) forming the array, the periodicity of the holes (or rods), the lattice structure, the thickness of the material and the refractive index.

The properties of photonic crystals can be understood by making an analogy with semiconductors. In general in a semiconductor the valence or conduction electrons can move in a periodic potential arising from the positively charged ion cores (the nucleus). The potential is characterised by two areas of allowed energy, which are separated by a region of forbidden energy, called the energy gap, which means that there are certain wavelengths that will not propagate in the lattice (i.e. no electrons will be

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found in the band gap region). This is true for a perfect silicon crystal. However, for real materials the situation is different: electrons can have energy within the band gap if the periodicity of the lattice is broken. This can be the result of a missing silicon atom, or the presence of an impurity atom occupying a silicon site, or if the material contains interstitial impurities (additional atoms located at non-lattice sites). Doping of semiconductors is intentionally done in microelectronics.

Now consider photons moving through a block of transparent dielectric material that contains a number of tiny air holes arranged in a lattice pattern. The photons will pass through regions of high refractive index – the dielectric – alternating with regions of low refractive index – the air holes. This is analogous to the periodic potential that an electron experiences when travelling through a silicon crystal. If there is a large contrast in refractive index between the two regions then most of the light will be confined either within the dielectric material or the air holes. This confinement results in the formation of allowed energy regions separated by a forbidden region – the so-called **photonic band gap**. Since the wavelength of the photons is inversely proportional to their energy, the patterned dielectric material will block light with wavelengths in the photonic band gap, while allowing other wavelengths to pass freely.

In a semiconductor it is possible to break the perfect periodicity of a silicon-crystal lattice by introducing defects (doping), and to have electrons in the forbidden energy gap region. Similarly, it is possible to **create energy levels in the photonic band gap** by changing the size of the holes (or rods) forming the photonic crystals. This introduces an “allowed frequency” (which means an allowed wavelength) in the photonic bandgap, and the photonic crystal then acts like a waveguide.

Therefore in simple words semiconductors consist of periodic arrays on the atomic scale that control the flow of electrons; photonic crystals consist of periodic arrays on the scale of wavelength of dielectric material that control the propagation of light waves. Periodic structures made with materials having different dielectric properties (high and low refractive index materials) serve as waveguides. Optical properties can be kept absolutely under control by controlling the structure and material composition of the photonic crystal.

Fabrication of photonic crystals

There are different approaches to building a photonic crystal. The first researchers to report this idea were Yablonivich and John in 1987, who fabricated a crystal for microwave wavelengths. The fabrication consisted of covering a block of dielectric material with a mask consisting of an ordered array of holes

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and drilling through these holes in the block on three perpendicular facets. The material, which became known as "Yablonovite", prevented microwaves from propagating in any direction – in other words, it exhibited a 3-D photonic band gap. Despite this early success, it has taken over a decade to fabricate photonic crystals that work in the near-infrared and visible regions of the spectrum. For instance, for visible light a lattice dimension of 500nm approx. would be required, which means fabricating a material with holes separated by 500nm. This is an extremely difficult task which requires suitable materials and processing techniques.

Instead of drilling holes on a surface, another approach to creating a photonic crystal is to build the lattice out of isolated dielectric materials that are not in contact, as illustrated in **Figure 3**.

If an entire line defect is introduced in the lattice in **Figure 3** by removing an entire row of rods, the regions where the rods have been removed act like a wave guide, and an allowed energy level is created in the photon gap. A wave guide is like a pipe that confines electromagnetic energy, enabling it to flow in only one direction. One interesting characteristic of such a wave guide is that light passing though it can turn very sharp corners, which is not true in an optical fibre.

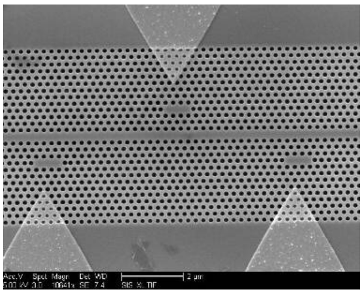

Figure 3. A scanning electron microscope image of a photonic crystal. The periodic arrangement of the holes in the material controls the movement of light within the crystal. Each hole has a diameter of about 200 nm. (Image credit: A. Faraon, Stanford University, NISE Network, www.nisenet.org, licensed under NISE network terms and conditions.)

If only one rod is eliminated in the lattice in Figure 9 (or if its diameter is changed), a resonant cavity is formed, which also puts an energy level into the gap. As mentioned before, this energy gap depends on the radius of the rod, which provides an opportunity to tune the frequency of the cavity. This ability to tune the light and concentrate it in small spaces makes photonic crystals useful for **filters and couplers in lasers**.

In theory, photonic crystal applications reach across the entire electromagnetic spectrum, from UV to radio waves. In practice the challenge is the nanofabrication of these devices. Novel nanofabrication methods, including self-assembly approaches, will play an essential role in the development of this field.

Displays

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Display technology has progressed enormously in the last decade. Until few years ago, we had bulky televisions with Cathode Ray Tube (CTR) technology, and mobile phones with black and white displays that could show only text. Nowadays, LCD televisions are becoming the norm and mobile phones that can show photos and movies are the norm, many even with touch-displays. This progress has been enabled by intense research in the field which is driven by a billion-dollar industry and the constant need for more functional devices combining, that combine portability, image and video quality, low power consumption and low cost. Thickness and flexibility are also becoming an important requirement. Here we review some latest advances in display technology and the impact that nanotechnologies have in their development. We will describe in detail **Organic Light Emitting Diodes (OLEDs)**, **Quantum Dot Light Emitting Diodes (QD/LEDs)** and **electronic paper (e-paper)**. Another area of development is **Field Emission Displays (FED)** which in a sense are the progression of the old Cathode Ray Technology to the nanoscale. FED uses an element, like carbon nanotubes, as a source of electrons that strike a coloured phosphor. This technology is not commercial yet and remains at prototype level.

OLEDs

Current displays rely mainly on two approaches: Liquid Crystal Display (LCD) and Plasma Display Panel (PDP). Those two technologies have basically replaced the old cathode tube technology for displays, which is being phased out. PDP requires much more energy than LCD to operate and is currently not as successful as LCD, especially in a time when energy consumption is a major concern. LCD technology on the other hand is becoming extremely common due to a considerable price drop in the last few years.

LCD displays offer a number of advantages compared to the old cathode tube technology: first of all, displays are much thinner and less bulky due to their inherent structure and assembly, and they provide a much better image quality. However, **LCDs** have two main problems that are connected to their inherent composition: first, LCD displays can be **difficult to see at oblique angles**, as laptop computer users are well aware; second, they require backlight, which consumes power.

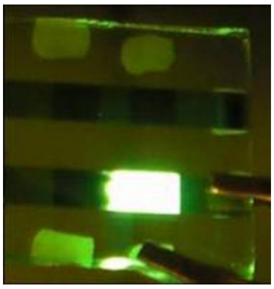

Figure 4. OLED films about 200nm thick. (Image credit: R. Ovilla, University of Texas at Dallas, NISE Network, www.nisenet.org, licensed under NISE network terms and conditions).

The need for backlight explains why in an LCD black looks more like deep gray than true black.

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OLED have emerged as a new technology that offers a number of advantages compared to LCD. In this technology, the display is formed of an emissive and conductive layer sandwiched between an anode and a cathode. A voltage is applied across the OLED so that the *anode is positive* with respect to the cathode. This creates a flow of electrons from the anode to the cathode; therefore electrons are removed from the conductive layer and added to the emissive layer. The conductive layer becomes positively charged and the emissive layer negatively charged. This causes electron holes to appear at the boundary between the two layers: electrostatic forces induce electrons and holes to get closer and they recombine, emitting energy as a photon. Emission is in the visible region and this is what generates the colours in the display.

Molecules used in OLEDs – as the name suggests – are organic molecules like organo-metallic chelates and conjugated dendrimers (two types of macromolecules that can reach the nanoscale). The molecules can be directly evaporated or printed on the polymer substrate, which is a notable advantage, and can lead to very complex multi-layer structures. The molecules are deposited in rows and columns onto the flat carrier (simply by printing) and the resulting **matrix of pixels can emit different colours**.

Therefore the **colour generation in an OLED** is fundamentally different from that in an LCD, which is powered by a fluorescent lamp (backlight) that is colour-filtered to produce red, green and blue pixels. Thus, when an LCD screen displays full white colour, two-thirds of the light is absorbed by the filters. This explains some fundamental **advantages of OLEDs over LCD**:

- **OLED pixels directly emit light**, it does **not require backlight**, thus consuming less power than LCDs. When in the OFF mode the OLED elements produce no light and consume no power.

- OLEDs have a much better picture quality because they **naturally achieve a higher contrast ratio**. For a viewer the most noticeable effect is that the black areas in an OLED appear true black.

- OLEDs can be much **thinner and lighter** than LCD panels. In addition, OLED can be printed onto any suitable substrate using an inkjet printer so they can theoretically be incorporated into flexible substrates, which opens up numerous new display possibilities (roll-up displays or displays included in fabrics).

- Unlike LCDs, OLED panels can be seen well **under sunlight** and at different angles.

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OLED technology is currently used in small displays (OLEDS are used in numerous colour mobile phones) but is not yet established in television panels due to some **challenges** that OLED technology encounters. Many of these challenges can be addressed with the use of nanomaterials and nanotechnologies.

First, the organic molecules used in the OLED have an inherent tendency to degrade in time. Increasing the **lifetime** of OLEDs is a research priority. This is particularly true for the blue colour (for instance the lifetime of a blue OLED is 14,000 hours whereas a typical LCD panel has a lifetime of 60,000 hours). Much research is being dedicated to the synthesis and testing of new organic molecules that can increase the lifetime of OLEDs. The problem of OLED lifetime is particularly important in those electronics that require long lifetime (e.g. televisions). In devices that are used intermittently (mobile phones, etc.) lifespan is less important. This explains why OLED technology is already fairly well diffused in mobile devices.

A second problem is in the nature of the top cathode layer of the OLED, which needs to be a transparent electrode. Currently, ITO (Indium Tin Oxide) is used since it offers a combination of conductivity and transparency. The problem is in the availability of ITO, which is declining, and in the way it is processed, which is done using chemical vapour deposition (CVD). This deposition method requires very high temperatures which limit the type of substrate that can be used. ITO is slightly opaque and this affects image quality. A very active field of research is the search for **suitable nanomaterials to replace ITO** in OLED cathodes. One possibility is carbon nanotubes. Currently there are numerous methods to fabricate CNTs (alternatives to CVD) like spray coating and roll-to-roll printing. Also numerous companies are emerging that produce CNTs and the price is dropping.

Another issue in OLEDs is that the organic molecules contained within them are **very sensitive to water** and other substances. Therefore coating and packing of the OLED components is of fundamental importance. One of the problems is that current packaging materials are either too brittle (which is a problem in flexible screens) or require too high temperature during their production process, which would destroy the device. Currently, alternating layers of organic and inorganic materials are used. This gives some level of flexibility and blocks the entry of foreign substances (although not totally). **Nanomaterials** could help solve this challenge: for instance, a method was recently developed where nanoparticles are used to fill the pores in these organic and inorganic layers, which remarkably improved the packaging of these devices.

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Application of OLEDs

OLED technology can be used for two main applications: displays and light sources. The possibility of using OLEDs instead of traditional light bulbs is very attractive in terms of energy consumption (conventional incandescent lights lose most of their energy as heat). OLED technology is thus being considered for use in lights and signs. The potential of OLED technology in the energy sector is discussed in **Chapter 3 ("Application of nanotechnologies: Energy")**.

The second mainstream application is in the **display industry**. Currently they are used as small screens for mobile phones, portable digital audio players (MP3), car radios, digital cameras, etc. **OLED technology in TV** is just appearing on the market. The first commercial OLED TV was the Sony XEL-1, commercialised in 2007 (in the US at a cost of about $2,500). In October 2008 Samsung announced the world's largest OLED Television (40-inch) with a Full HD resolution of 1920x1080 pixels. The same company showcased the thinnest OLED display, only 0.05 mm, meaning thinner than paper. This opens up numerous opportunities. Clearly all major display companies are investing a lot in this new technology.

The fact that OLED can be fabricated on flexible substrates opens the door to **OLEDs in textiles**, **labels** and other flexible materials.

Quantum Dot Light Emission Diodes (QD/LED)

Quantum dots (QD) are another class of nanomaterials that are under investigation for making more efficient displays and light sources (QD-LEDs). These are nanoscale semiconductor particles characterised by emitting a specific colour based on the size of the nanoparticle. A minute change in particle size results in a totally different colour being emitted; for instance a 6 nm-diameter particle would glow red, while another of the same material but only 2 nm wide would glow blue. Light emission from a QD is monochromatic, therefore it is very pure. As a consequence, their use in displays would lead to images of exceptional quality. The most exciting property of QD-LEDs, however, is that they use much less power than currently employed LCDs where light is filtered by numerous polarisers. Like OLEDS, QD LEDs emit light, rather than filtering it, so for this reason QD-LEDs are expected to be more energy efficient. In June 2006, QD Vision announced a first proof of concept of a quantum dot display.

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Electronic paper (e-paper)

E-paper is a display technology that aims at mimicking the appearance of ordinary ink on paper. There are various technologies to create an e-paper, among which **electrophoretic paper** is the most established. Unlike conventional flat panel displays, electrophoretic displays rely on reflected ambient light, rather than emission of light from the display, and can retain text or images without constant refreshing, thereby requiring much less power. This means also that they can be used under sunlight without the image fading. E-paper is also very **light** and **flexible**.

E-paper has numerous commercial applications, such as **e-books** (meaning e-readers that can display the digital version of a book), **e-papers**, **electronic labels**, general signage, timetables at bus stations, etc.

The first electronic paper was invented in the 1970s by Nick Sheridon (Xeron) and was called Gyricon. The technology behind electrophoretic paper is fundamentally different that that behind other displays. Here the information display is formed by the rearrangement of charged pigment particles in an applied electric field. The particles are **titanium oxide (TiO_2)** about 1 micrometer in diameter, dispersed in oil where a **dark-coloured dye** has been added, together with surfactants and charging agents. The mixture is placed between two parallel conductive plates and a voltage applied. The charged particle move electrophoretically towards the plate with their opposing charges. When the particles are on the front side of the display, they scatter light and appear white; if they are at the back of the display, it looks black because the incident light is absorbed by the dye. The back electrode is divided into a number of small picture elements, the pixels, so the image is formed by delivering the appropriate voltage to the pixel (resulting in a white or black pixel). Therefore the image is created by a repeated pattern of reflecting (white) and absorbing (black) regions.

Figure 5. Gyricon e-paper rolled up. (Image credit: Eugeni Pulido, Wiki Commons, Creative Commons Attribute ShareAlike 3.0)

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Figure 6. An example of an e-paper device (Image credit: Manuel Schneider, Wiki Commons, Creative Commons Attribute ShareAlike 3.0)

Developers imagine that e-paper will be used as a support (imagine a roll to keep in your pocket that opens up on command) on which to download information (from an overhead satellite, a mobile phone network or an internal memory chip) and then as a reading support which does not require power and can be seen under sunlight, etc. Once reading is done, the device can be rolled up again, placed in the pocket and re-used.

At the moment the technology is limited to black and white but numerous companies are investing a lot to develop a coloured e-paper solution. Another issue is its low refresh rate, making electrophoretic paper **unsuitable for displaying animation or video**. Some newspapers are already offering their subscriber's e-paper versions of their prints.

Nanotechnologies for e-paper

Some new materials are emerging as elements of e-paper. In May 2008 Unidym and Samsung produced the first active matrix **e-paper device incorporating carbon nanotubes** as the transparent electrodes. Other approaches use photonic crystals, liquid crystals and other nanomaterials.

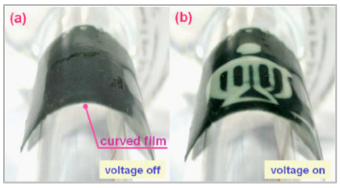

Figure 7. A thermochromic display under development at the Hong Kong University of Science and Technology. (Image credit: reprinted with permission from Liu et al., "paperlike thermochromic display", Applied Physics Letters (2007), 90, 213508. Copyright © 2007 American Institute of Physics.)

Another development uses a **thermochromic display** which can easily be fabricated using soft lithography. The thermochromic material is a microencapsulated powder mixed inside a polymer (PDMS). The thermochromic material is dark green at room temperature but turns white when heated above 60 °C. Once the two components have been mixed, they form a polymer composite that can be spin-coated over a substrate and, once it is cured, it forms a thin polymeric sheet that has the characteristic (inherent to PDMS) of being very flexible but also resistant to stretching, etc. The thermochromic display is basically made of a single layer of thermochromic sheet in which a conductive wire, which is shaped in the logo desired, is embedded. When a voltage is applied, an electric current is generated in the wire, which creates a localised heat. Above 60 °C, the colour of the thermochromic composite in the area corresponding to where the wire is becomes white, and the image of the logo appears. The main limitation of this technology is that the image is created through a wire, and not pixels.

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Information storage devices

Numerous miniaturised devices now exist that can store and transmit data. Two examples are "smart cards" and "smart tags". These devices have been created to meet the need to collect and transmit data using less space (chips) and wirelessly. The application of these devices covers personal data cards (e-patents, e-health cards, credit cards, etc.), tags for package protection and tracking, etc. The trend in the development of these devices has been the one opened up by miniaturisation: integration of more functions in a smaller space. In the future this trend will continue and nanotechnology will most likely be the enabling technology.

Nanotechnologies in tags

Products are most commonly **identified and tracked** using a label, which is also a code; the one still used commonly is the barcode. In the last years we have seen the emergence of another labelling and tracking system called Radio Frequency Identification (RFID). An RFID is a small, wireless integrated-circuit (IC) chip with a radio circuit and an identification code embedded in it. The advantages of the RFID tag over other scannable tags (like barcodes) are that the RFID tag is small enough to be embedded in the product itself (not just on its package); it can hold much more information; it can be scanned at a distance (and through materials, such as boxes or other packaging); and many tags can be scanned at the same time. RFID tags are already being used in many ways, for instance for **livestock tracking** (attached to the ear or injected into the animal) or in the latest **e-passports**. They are used in libraries, schools, transport systems (toll roads), tickets (parking tickets), sports (race timing), etc. Developers of the technology envision a world where they can "identify any object anywhere automatically."

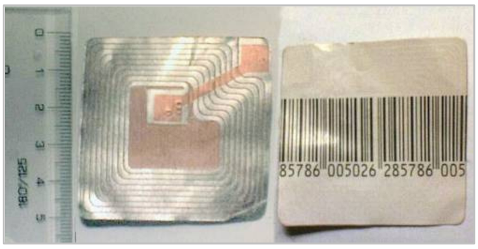

Figure 8. RFID chip on a stick with bar code on the opposite site (Image credit: Wiki Commons, Public image).

The current size of the RFID chip is now about the size of a dust mite, the smallest is about 50 x 50 μm. There are already some developments that make use of nanotechnology, in particular in tags that are directed towards the authentication and tracking of valuable products such as drugs. The goal is to avoid counterfeiting and to make sure that the drug is not released into the wrong market (e.g. black market). One example is a technology developed by NanoInk®, the company that owns the patent of the Dip Pen

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Nanolithography (DPN)[2] instrument, which was invented by the company owner. The company had developed a technique for **encrypting pills** using the DPN. Each pill can be encrypted with information about place and day of manufacture, target market and expiry date. To make this encrypting technology fully workable, the same encrypting should be placed on the package of the drugs. Another method developed at the National Physics laboratory in the UK makes use of electron beam lithography to encrypt pills. This way the pill carries information in a very secure way: a special reader is needed for it to be decoded. Also, the information is so tiny that it cannot be seen with the naked eye, making it ideal for covertly marking things.

Another strategy for authentication, developed in particular for packing, has been developed by Nanoplex Technologies (US) in the form of nanobarcodes. These are made of nanoparticles of gold, silver and platinum, which are grown into strips. Each stripe has a different metal combination which leads to a different reflectivity of the stripe. A special microscope reader is needed to decode the information. **Nanoplex** can create different codes by alternating the stripe order. Billions of different codes can be made. Each unique code can be associated with an item, which allows the company to track where the item is or has been.

ELSA TOPIC: Developers of RFID technology imagine that one day we could place an RFID invisible tag on every object, to follow its location, transport, but also to ensure (in the case of food packages) the product integrity, etc. RFID technology could be the ultimate solution to theft and fraud. However, in some cases RFID chips have been implanted into humans; for instance in 2004, the Mexican Attorney General's office implanted 18 of its staff members with one such chip (called Verichip) to control access to a secure data room. The use of RFID implantable chips is strongly opposed by privacy advocates and some human right movements like Friends of the Earth, warning of potential abuse. They have denounced these devices as being "spychips" which could be used by governments, leading to an increased loss of civil liberties. If private employers were to use this type of chips on their employees they would have access to an incredible amount of private information. In addition, privacy advocates say that the information contained in this chip could easily be stolen, so that storing anything private could lead to identity theft. In terms of safety, the Food and Drug Administration warned in 2004 that these chips pose potential medical problems. Electrical hazards, MRI incompatibility, adverse tissue reaction, and migration of the implanted transponder are just a few of the potential risks the FDA has identified with the Verichip ID implant device.

[2] *For details on the DPN and its function, see Chapter 7 of Module 2 "Fabrication methods".*

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Wireless sensing and communication

At the moment "electronics" for us means basically devices, pieces of equipment that can offer us a service (computation, information, entertainment and communication). The development path as we have seen it in the last years has been adding performance and complexity to these devices. One of the visions in the ICT industry is the concept of **ambient intelligence**: computation and communication always available and ready to serve the user is an intelligent way, meaning satisfying certain requirements. The vision is that electronics will be embedded in our natural surroundings (clothes, books, doors, etc.), present whenever we need it, enabled by simple and effortless actions, attuned by our senses, adaptive to users' needs and actions, and totally autonomous. The concept of ambient intelligence is partly still a science fiction vision, and technologies are not yet developed that allow this vision to be realised. However, the vision of actively interfacing humans and electronics is not totally abstract: think for instance of the Wii system, which allows a person to command (and play with) software simply by moving at a distance, or virtual reality games and communication tools. The vision of ambient intelligence, however, is even more ambitious. Scientific progress and industrial investment are likely to make ambient intelligence (or at least some of its concepts) a reality in the future.

Electronic devices in the "intelligent ambient world" will become a gateway between the user and the environment. A fundamental requirement is **ubiquitous sensing and computing**: devices must be highly miniaturised, integrated in the environment, autonomous, robust, and require low power consumption. They should be created easily and survive without particular management. All of these requirements are likely to be met with the use of nanotechnologies; below we list some key elements:

- **Miniaturisation and system integration**: Numerous different functions (logic, memory, radio frequency, sensors and software) will need to be integrated in a single component. This implies new and severe demands on the microelectronic, opto-electronic and microsystem components that are the "building blocks" of the Information Society technologies. It means developing new manufacturing technologies and materials that can make it possible to reach this advanced system integration at feasible costs. Nanotechnologies allow use of nano-sized material (carbon nanotubes, molecular electronics, etc.) and realise nano-system transistors hundreds of times smaller than the current ones. Miniaturisation is the gateway to reach a number of key elements: mobility, low power consumption, more performance, small sizes and low weight, low cost, high reliability, more flexibility and ubiquity.

- **From "chips" to embedded "soft" electronics**. Electronics now are in the form of solid, rigid "wafers" or "chips". To realise the concept of ambient intelligence a key requirement is embedding electronics in

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many different types of materials, from plastics to textiles. Organic electronics (meaning naturally conducting molecules, such as polypyrrole) will have an important role. At the moment, organic materials are used in OLEDs (see dedicated section in this chapter), organic solar cells (discussed in **Chapter 3 of this Module 2 "Application of Nanotechnologies: Energy"**), and in organic transistors (still at a proof-of-concept stage). Although all these systems are still in development, research is very intense and it is likely that organic electronics will become a key component in our future electronic devices. The reason is that organic electronics are produced by depositing and patterning thin films of organic conductors, semiconductors or insulators. Organic films can be deposited in a vacuum, but also inexpensively from solution or via high-resolution ink-jet printing. Processing temperature is always low (below 200°C) meaning that organic thin films can be integrated with soft materials like plastics, opening the way to flexible organic electronics.

- **Embedded sensors**. One of the key enablers of ambient intelligence is the presence of sensors embedded in the user and in the environment it needs to communicate with to gather information and communicate data wirelessly. Nanotechnologies may render this possible by enhancing the sensory skills of humans based on **wearable or embedded sensors** (for instance in clothing) and the ability to process this enormous amount of sensory data through powerful computers. In order to achieve a true integration between the sensor element and the physical object the device should adapt to the environment that surrounds it: basically those devices should become "intelligent" in the sense that learning should be a key property of their system, similarly to the way systems grow and adapt in the biological world. Ambient sensors should also be robust, survive in harsh environments or in the case of wearable electronics survive washing, be inexpensive and be ecologically sustainable.

- **Integrated power sources**. Power supply is crucial for all embedded electronics, whether wearable (e.g. electronics in clothing, shoes, etc.) or embedded in objects surrounding the user. For instance in the case of wearable electronics, where low powers are required, the electrical power could be either body heat or body movement. Although the field is in its infancy, research is very intense and some systems have been demonstrated in laboratories in the form of miniaturised thermogenerators or miniaturised energy scavenger systems (these are discussed in **Chapter 3 of Module 2 "Application of Nanotechnologies: Energy"**).

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ELSA TOPIC: Clearly the realisation of the vision of ambient intelligence requires meeting numerous scientific and technical challenges. The time frame from "vision" to reality could be decades. In addition, the concept itself brings about a number of fundamental ethical and social questions: what does it mean to be human? What does it mean to "sense"? Is it ethical to enhance (and interfere with) the way humans interact with their environment? Does human progress "need" this technology? Questions of personal data privacy also arise. The questions are numerous and intense discussion on these fundamental ethical issues is already taking place. Nanotechnologies, being an enabler of the ambient intelligence vision, are necessarily part of these discussions.

Wearable sensing textiles

Sensors could be inserted inside our clothes to gather information about our location and other environmental conditions around us, such as temperature, pressure, etc. This would enormously facilitate the task of locating missing people. For instance a jacket (or other wearable textile) with an integrated GPS sensor could become a standard part of children's clothing to ensure their safety. Other electronics could become integrated as well, such as phones, music devices, etc. With the advancement of nanoelectronics those types of clothing could become a reality.

***NANOYOU DILEMMA**: The example of the jacket with an embedded GPS represents the base for one of the NANOYOU dilemmas, part of the **NANOYOU Role Play Card Game** (see www.nanoyou.eu/en/decide). Imagine this jacket used for children's clothing: it would allow parents to always know the location of their children. If they get lost, they could be immediately located. However, would it make them feel that were under constant surveillance? Is this against the fundamental human right of freedom?*

Intelligent sensors are already a reality in the form of **wearable sensing textiles** that can monitor fundamental physiological parameters like heart rate, temperature, respiratory rate, etc., with applications in monitoring and prevention of cardiovascular risk. For instance the Italian company Smartex has developed a prototype that measures all of these parameters, including posture. The information registered by the sensing textile is sent to a computer via Bluetooth. The company is also part of a new European project called Biotex which aims at creating wearable textiles with even more sophisticated sensing capabilities. The aim is to create **biosensing clothes** that provide remote monitoring of physiological and metabolic functions to improve early diagnosis. The approach aims at developing sensing patches adapted to various targeted body fluids and biological species to be monitored, where the textile itself is the sensor.

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