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REVIEW ARTICLE

Advances in Nanoelectronics: Carbon Nanotubes, Graphene, and Smart Polymers: A review

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Abstract

In recent years, in order to miniaturize electronic devices, reduce manufacturing costs and increase the efficiency of electronic and optical systems, a new field called "nanoelectronics" has been developed. In this field, silicon is no longer used as the main component of systems, and this unique material has given its place to biological, organic and mineral materials. For this reason, the general principles of design in nanoelectronics devices are subject to new parameters, each of which can lead to the development of new properties, characteristics and applications. Nanoelectronics science seeks to miniaturize traditional electronic devices and increase their efficiency. So far, a comprehensive classification for the main sub-branches of nanoelectronics that all scientific authorities follow has not been provided. However, nanoelectronics can be considered in several broad areas: 1) Nano sensors; 2) lab-on-a-chip; 3) artificial organs; 4) bionics and biomimetic; 5) imaging; 6) integrated circuits and 7) molecular nanoelectronics. Organic materials are those materials that have a continuous structure of carbon-hydrogen bonds. So far, more than 16 thousand types of organic substances with different molecular and chemical structures have been produced. One of the main applications of this category of materials is their use in the manufacture of nanoelectronic devices. In this way, a field in electronics called "organic nanoelectronics" has been developed. But so far, only a limited number of these materials have been able to be used in organic-based nanoelectronics devices. These materials include: organic charge transfer complexes, conductive or conjugated polymers with π bonds, conductive gels, and dielectric polymers. The reason for the importance of each of these types of materials is their electrical properties and unique structure. Carbon nanotube is used in many nanoelectronics devices due to its crystallographic structure and unique properties. Due to its significant surface area, hollow structure, high mechanical strength, excellent electrical properties, and unique structures in electron bonds, this material is widely used in energy storage, nanocomposite materials, and making nanoelectronics devices such as Nano sensors.

Keyword: Carbon nanotube, Electrical conductivity, Nano transistor, Graphene, DNA, Sequencing, Nanoelectronics, Organic, Inorganic, Microelectronics, Bionic, Sensor, Graphene nanoribbons, Molecular nanoelectronics, Nanopore DNA sequencing

Introduction

Carbon structures have a wide range of properties due to the specific chemistry of carbon atoms [1-5]. Carbon is the main component of some important nanoelectronics compounds such as diamond, amorphous carbon, fullerene, carbon nanofibers (CNFs), carbon nanotubes (CNTs) and graphene. Cytologically, carbon nanotubes are cylindrical tubes made of graphene sheets [6-11]. These materials can be made with one wall (Single-Walled Carbon Nanotube, SWNTs) or multiple walls of tubular graphene sheets (Multi-Walled Carbon Nanotubes, MWNTs). **Figure 1** shows different types of carbon nanotubes [10-12]. Single-walled carbon nanotubes are made from a single-layer graphene sheet in the form of a cylinder with a diameter of 1 to 2 nm. Multi-walled carbon nanotubes also consist of dense and closely packed graphene tubes with multiple layers of graphene sheets [12-16]. These materials have a cavity with an approximate diameter of 2 to 25 nm, and other rings are placed concentrically with a distance of 0.34 nm from each other.

By changing the structure, diameter, and orientation of carbon nanotubes, the electrical behavior of these materials can be changed from metallic to semiconducting [17-22]. The mechanical and microstructural properties of nanotubes are highly dependent on their geometric size, crystal structure, and topography. Scientific observations have proven that carbon nanotubes, along with good chemical stability, have very high tensile strength (100 times that of steel) and extraordinary Young's modulus (7 times that of steel) [23-26]. The reason for such excellent mechanical properties in carbon nanotubes is its formation from sp^2 hybridized carbons. In addition, carbon nanotubes are very light and their thermal stability reaches temperatures higher than 1,000 °C [27-31]. The high thermal conductivity of carbon nanotubes is another prominent property of these nanostructures. The thermal conductivity of these materials is reported to be almost twice that of diamond. Another important phenomenon in carbon nanotubes is the dependence of the movement of charge carriers along the nanotube on the arrangement of electrons, which causes semiconducting or metallic properties in these materials [32-36]. **Figure 2** lists the salient properties of carbon nanotubes. So far, various methods have been proposed for the synthesis of carbon nanotubes, the most important of which are the following [31-35]:

1) Laser ablation
2) Catalytic decomposition of hydrocarbons
3) Metal Organic Chemical Vapor Deposition (MOCVD)
4) Electrical arc discharge
5) High pressure CO conversion

In addition to electronic applications of carbon nanotubes, these materials are used in other industries such as composite materials, coatings and films, energy storage, environmental issues, and biotechnology [37-42]. **Figure 3** shows the number of published documents (patent) about the application areas of carbon nanotubes.

The term graphene was first introduced in 1986. This word is a combination of the word "graphite" and the suffix "en". "en" refers to polycyclic aromatic hydrocarbons [43-45]. Graphene is a 2-dimensional sheet of carbon atoms in a hexagonal or honeycomb pattern, where the atoms are bonded together by sp^2 hybridization. Graphene is the newest member of the family of multidimensional graphitic carbon materials. Graphitic carbon materials include fullerene (0-dimensional), carbon nanotubes (1-dimensional) and graphite (3-dimensional) [46-50]. These plates are formed by placing carbon atoms together. In a graphene sheet, each carbon atom bonds with 3 other carbon atoms. All these links are on the same plane and make angles equal to 120 degrees. The length of carbon-carbon bonds in graphene is reported to be about 0.142 nm. Single-layer graphene is the main motif of carbon structures, which means that graphite is formed by stacking graphene sheets, carbon nanotubes are formed by its tabularizations around an axis, and fluorene is formed by wrapping it into spheres. Graphene layers consisting of 3 to 10 layers are called "thin layer graphene" and between 10 to 30 layers are called "thick multilayer graphene" or "thin graphite nanocrystals" [51-54]. **Figure 4** shows a diagram of the graphene crystal lattice. Since the discovery of graphene, many physical and chemical methods have been developed to produce different types of single-layers and multi-layer graphene, the most important of which are the following [51-54]:

Bottom-up methods
1) Chemical Vapor Deposition (CVD)
2) Epitaxial growth
3) Pyrolysis

Top to bottom washes
1) Atomic force microscope
2) Mechanical exfoliation
3) Revival or reduction
4) Chemical synthesis

So far, the mechanical properties of monolayer graphene, including elastic modulus and fracture strength, have been studied by numerical simulations and molecular dynamics. Research has shown that the Young's modulus of a defect-free graphene is 1 tera pascal and its fracture toughness is 130 GPa. Recently, the elastic properties and intrinsic fracture toughness of monolayer graphene have been measured using atomic force microscopy (AFM) [55-60]. According to some studies, graphene is the strongest material ever identified. In addition, graphene is a very light material with a weight of 0. 77 $mg.m^{-2}$. To put it in perspective, a bed with an area of one square meter of graphene can support a 4 kg cat, while it weighs the same as a strand of cat hair. So far, many studies have been conducted on the optical properties of graphene. According to the reported results, graphene initially produces a very opaque layer in vacuum and absorbs approximately 2.3 % of white light. Adding another layer of graphene increases the amount of absorption of white light up to twice the amount of absorption of single-layer graphene [61,62]. When the light intensity reaches a critical value, saturation in absorption occurs [60-63]. **Figure 5** shows a 50 μm gap covered with 2 successive layers of graphene. The linear scan profile shows the intensity of white light transmission along the yellow line. As shown in the figure, the amount of light transmittance has been reduced to 3.2 % by applying a graphene layer. By depositing another layer on top of the previous layer, which is marked as bilayer in the figure, it leads to a decrease of 4.6 % of the transmitted light. So, by increasing the number of graphene layers, the amount of light absorption increases [64-70]. Due to its unique properties, graphene is used in the manufacture of many delicate nanoelectronics and nanotechnology devices. The most important of these applications are electronic applications, strengthening applications in composites, electro-optical applications, medical engineering, targeted drug delivery and energy storage [71-74].

In the past centuries, organic materials were those natural materials that were used in human life and were not produced by laboratory methods. Hence, organic chemistry was also called "natural chemistry" (chemistry of life). Over time, the concept of organic chemistry was limited to the "chemistry of carbon compounds", especially the carbon structures found in coal. In the last century, the aforementioned concepts were developed and later, organic chemistry was called "the chemical study of carbon compounds and elements found in living biological species" [75-80].

The organic compounds we deal with today are often compounds found in the bodies of living organisms or their old carcasses. In the past, organic compounds were called oily substances obtained from the distillation of plants or alkaloids. Menthol is a famous example of aromatic compounds extracted from peppermint plant oil. Even in the 16th century, one of the famous alkaloids called "quinine" was extracted from the bark of trees in South Africa and used in the treatment of acute fevers. Quinine is one of the common organic substances [81-84]. The molecular structure of menthol and quinine is given in **Figure 6**. Coal was the main source of chemicals in the 19^{th} century. In those days, coal distillation often produced a brown tar that was rich in aromatic organic compounds such as benzene, pyridine, phenol, aniline, and thiophene. Since the burning of aromatic compounds produces hydrogen and carbon monoxide gas, these compounds were used to produce light and heat [85-89]. **Figure 7** shows the molecular structure of the most important aromatic organic compounds. Later, phenol was used as an antiseptic in surgery and aniline as the main ingredient in the production of industrial dyes [90-94]. After knowing the unique properties of some organic compounds, scientists tried to produce these substances in the laboratory, manipulate molecular structures, and produce special organic substances that did not exist in nature. Since then, the definition of organic chemistry as the chemistry of natural materials has been abandoned [95-100]. For example, the macromolecular organic compound Bismarck Brown (**Figure 8**) is an example of synthesized and unnatural materials used in the paint industry. is used. In the 20^{th} century, oil and petrochemical products emerged as the main source of production of organic compounds, and compounds such as hydrocarbons (methane, propane, etc.) were extracted from this valuable material. These organic compounds were mostly used as fuel. Since then, scientists have tried to produce or extract new molecules from other sources in nature such as fungi, bacteria, marine corals. So far, about 16 million organic compounds have been known [101-105]. These compounds are formed by increasing or decreasing constituent atoms, changing the atomic structure of molecules, or changing functional groups. These compounds are composed of molecules that have specific physical states depending on the type of bond and spatial arrangement relative to each other. In general, organic compounds may exist in one of the following forms: (a) crystalline solid; (b) oil; (c) wax; (d) plastic; (m) rubber; (N); Volatile liquid or fluid; and (x) gas. Certainly, in nanoelectronics applications, only solid or liquid organic compounds that have favorable electronic properties can be used [106-111].

The process of miniaturization of components of electronic equipment in the semiconductor industry has been very fast in the last 4 decades. In 1965, Gordon Moore predicted that the number of transistors that could fit on a chip would double every 2 years. This statement later became known as "Moore's Law". This law has been true so far and the number of transistors in a chip is increasing exponentially. Reducing the length of electronic components is necessary for the development of fully integrated circuits and faster processors [112-115]. On the other hand, Moore's 2^{nd} law states that the cost and difficulty of manufacturing silicon devices will increase exponentially, similar to their miniaturization process. Therefore, the problems caused by the miniaturization of silicon-based electronic devices can be summarized in the following cases [116-120]:

1) By reducing the dimensions of electronic components, the related costs and technical challenges

also increase, which in some cases cannot be solved [121-123].

2) With the miniaturization of electronic components to about 3 - 5 nm, heat dissipation increases to the extent that it can lead to melting of the equipment during service. The reason for this is due to the reduction of the cross-sectional area of the electronic components per unit area of the chip. In other words, miniaturization leads to a reduction in the cross-section of connections and transistors, and an increase in electrical frequency, the number of transistors, and the number of connections. Therefore, the current density passing through the chip surface unit increases and leads to an increase in heat loss. For example, in thicknesses less than 1 nm, SiO_2 used in silicon-based transistors is not insulating and generates a lot of heat, and this heat leads to a decrease in the efficiency of the transistor [124-128].

3) By reducing the dimensions of electronic units to the nanometer scale, their electrical properties become completely different from the electrical properties of bulk objects, and the probability of quantum phenomena increases. These quantum effects in smaller dimensions can interfere with the functioning of electronic equipment and disrupt its efficiency [129-133].

4) In order to reduce dimensions to the nanoscale, there is a need for methods that can produce and assemble the desired components with unique shapes and features so that nanometer components can be produced and combined to make macroscopic equipment. For example, existing lithography technology can only produce units up to 130 nm in size. Therefore, in order to produce microprocessors with smaller dimensions, the development of new nanolithography methods based on deep ultraviolet, X-ray and electron beam is needed [134-138].

Based on what has been said, Moore's law was only able to maintain its validity until 2005, and in order for it to remain valid, we should think about using new materials instead of silicon in electronic devices, and this point is the turning point of the field. Electronics and the development of the emerging field of nanoelectronics. The diagram in **Figure 9** shows the upward trend of transistor miniaturization in recent decades. According to this graph, the trend of miniaturization of electronic components has grown exponentially from 1970 to 2000, but since 2000, the growth rate of this trend has decreased [139-144]. The reason for this was the challenges and limitations mentioned above. The best way for Moore's law to remain valid is to use single molecules, self-assembled molecular layers, and nanoscale synthetic components such as graphene and carbon nanotubes as substitutes for electronic components. A branch of nanoelectronics in which single molecules or self-assembled molecular layers are used to design and build electronic systems is called "molecular nanoelectronics". The molecular units used include biomolecules and organic molecules. Therefore, based on the type of molecules, molecular nanoelectronics can be divided into 2 main sub-branches: "organic molecular nanoelectronics" and inorganic or inorganic molecular nanoelectronics [145-150]. Of course, due to the extensive use of biological units such as DNA, proteins, enzymes and cells in the construction of nanoelectronic devices, some researchers have developed an emerging branch under the title of "biological molecular nanoelectronics". This field is considered to some extent as a subset of organic molecular nanoelectronics [151-154].

In general, nanoelectronics pursues several main goals [155-160]: 1) miniaturization of electronic devices to the limit of several nanometers; 2) increasing the electronic efficiency of some devices; 3) designing very small electronic systems for the first time with some new and unique capabilities and 4) achieving some properties due to nano-sizing of material dimensions and proper exploitation of some nano-scale quantum phenomena. Many scientists believe that nanoelectronics has succeeded in achieving these goals, although there is a long way to industrialize some of the manufactured devices or optimize them [161-165]. **Figure 10** shows the trend of size changes of field effect transistors and dynamic random-access memories in recent years. **Table 1** also shows the changes in the volume of these memories and their cost for recent years. It can be seen that in recent years, nanoelectronics has been able to improve the efficiency and cost of electronic devices at the same time as they are miniaturized [166-170].

Therefore, a timely comprehensive review of the advances of carbon-based Nanoelectronics and their novel nanomaterials synthesis and composite design toward high performance is necessary. In this review, 3 categories of carbonaceous materials, including carbon nanotubes, reduced graphene oxide, and carbon fibers, have been tabulated and discussed. Their unique features, critical aspects of research, challenges associated with their synthesis and applications, and future prospective and study directions are introduced and discussed.

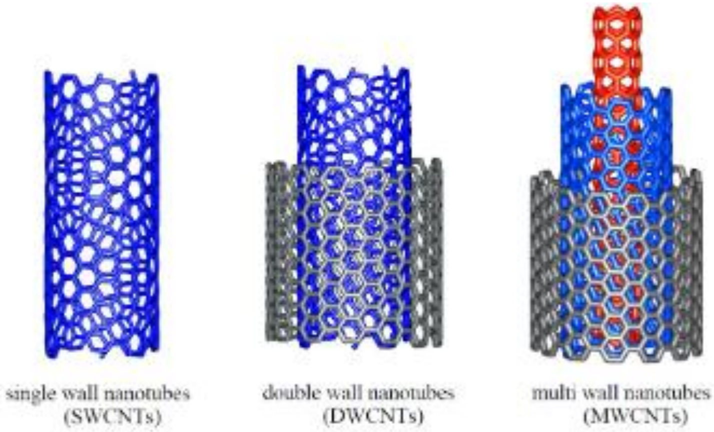


Figure 1 An overview of the types of carbon nanotubes, including single-walled, double-walled and multi-walled nanotubes [57].

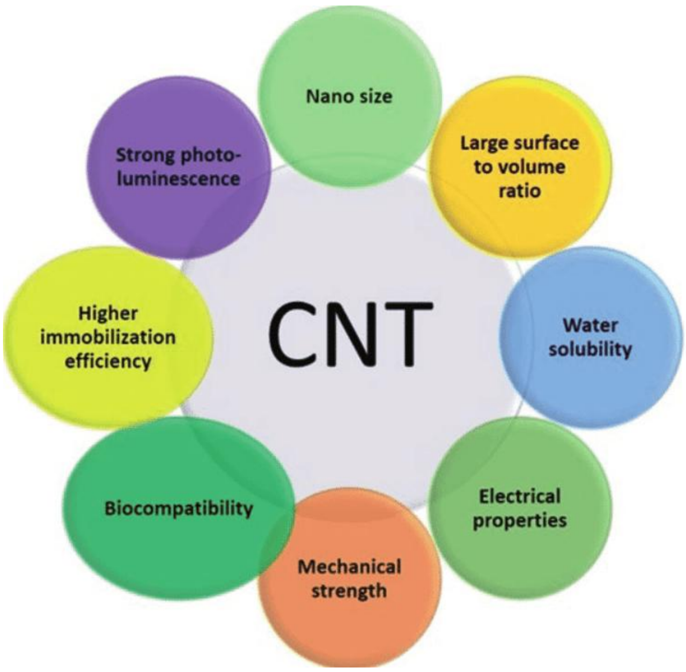


Figure 2 The most important properties of carbon nanotubes [58].

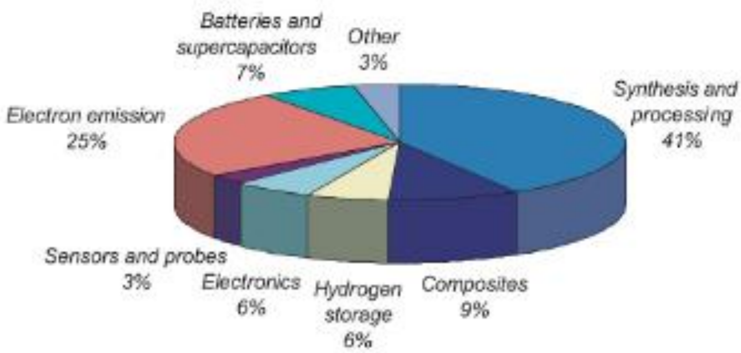


Figure 3 The number of published patents about the application areas of carbon nanotubes in the world [1].

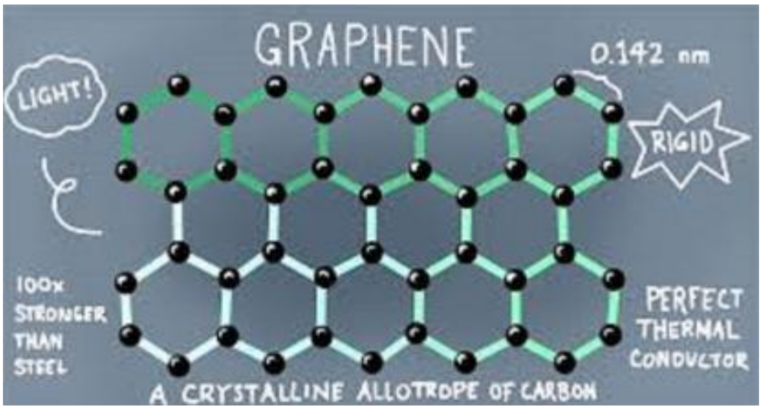


Figure 4 Diagram of graphene crystal lattice [1].

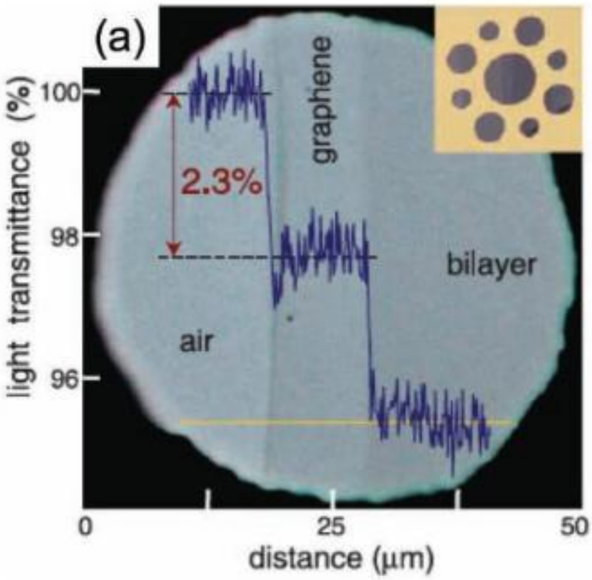


Figure 5 Image of a 50 µm gap on a silicon substrate coated with 2 successive layers of graphene. The linear scan profile shows the intensity of white light transmission along the yellow line. A sudden decrease in the amount of light transmission indicates the application of a graphene layer on the silicon substrate [1].

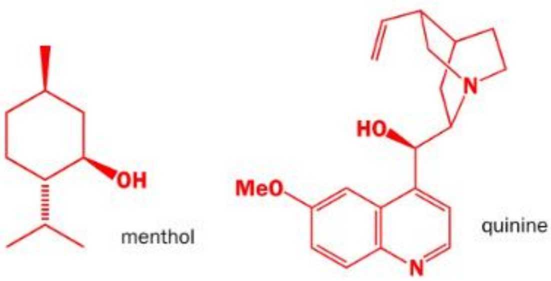


Figure 6 Examples of common organic compounds: menthol and quinine [59].

Figure 7 Molecular structure of the most important aromatic organic compounds including benzene, pyridine, phenol, aniline, and thiophene [59].

Figure 8 Molecular structure of Bismarck Brown [59].

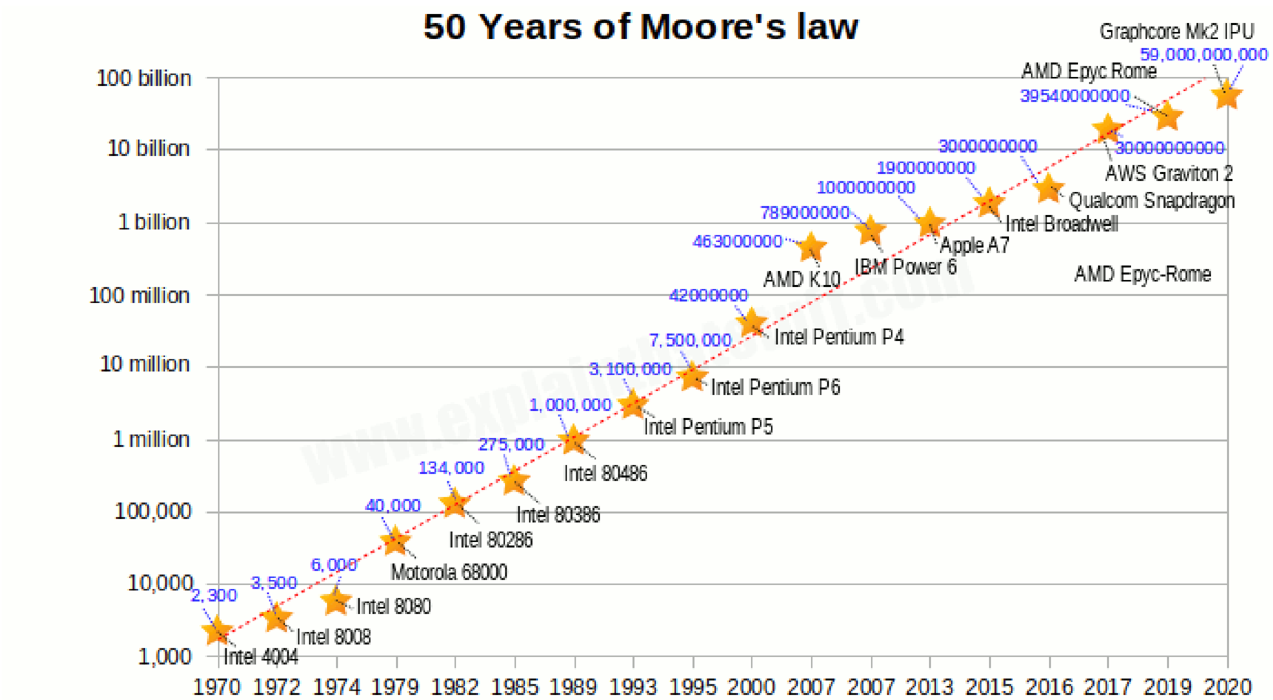


Figure 9 The process of exponential growth of the number of transistors used in a logic circuit [2].

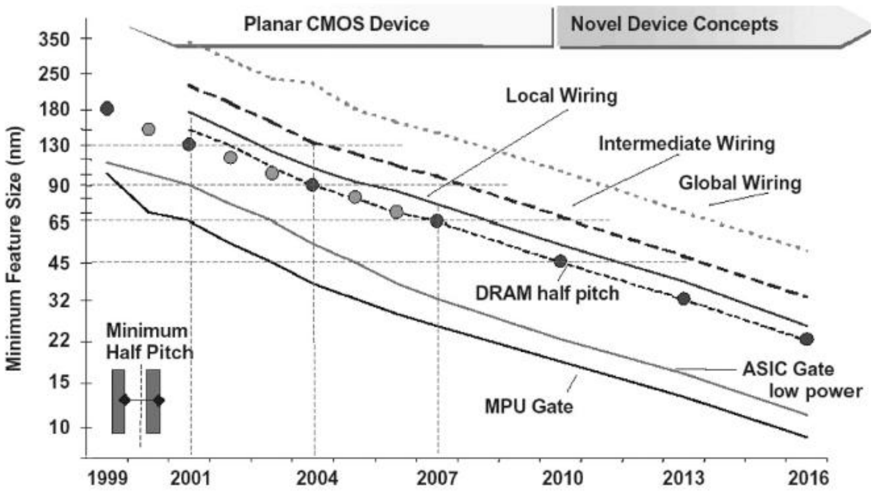


Figure 10 The process of reducing the dimensions of field effect transistors and dynamic memories with random access in recent years [52].

Table 1 The capacity of dynamic random-access memories (DRAM) and their cost in the last 2 decades [52].

Memories (DRAM)	1995(year)	1998(year)	2001(year)	2004(year)	2007(year)	2010(year)
Bits per chip	64 M	256 M	1 G	4 G	16 G	64 G
Cost per bit (milli -cent)	0.017	0.007	0.003	0.001	0.0005	0.0002
Cost per chip (US$)	11	18	30	40	80	130

Electrical properties of carbon nanotubes

Single-walled carbon nanotubes have a small energy gap of about 10 millielectron volts. This unique property has been observed for the first time in electron transfer measurements. Electron transfers in single-walled carbon nanotubes are performed by changing the gate voltage [170-174]. The electrical behavior of these materials can be metallic or semiconducting depending on the position of the Fermi level. Considering that carbon nanotubes are simple carbon structures, their electronic properties strongly depend on the diameter and chirality of the tubes. Researchers have proposed a simple tight-binding model to better understand the electronic properties of these materials [175-180]. In solid state physics, the tight-binding model is a simple method to calculate the electronic band structure using wave functions, based on the superposition of these functions, for isolated atoms located at an arbitrary atomic location. This method is very similar to the Linear Combination of Atomic Orbitals (LCAO) method used in chemistry [181-184]. The tight-binding model provides quantitatively acceptable results in many cases. Since this model is a one-electron model, it can be the basis for advanced calculations in the surface state. The conducted research shows that in addition to the change in diameter and chirality, structural changes can also affect the electronic properties of carbon nanotubes. It has been proven that uniaxial stresses do not have much effect on the interconnected structure of armchair nanotubes, while the interconnected structure of zigzag nanotubes changes significantly with these stresses. In fact, nowadays, in order to investigate the relationship between the electronic structure of nanotubes and applied mechanical strains, the changes in the π bond structure of graphene are studied [185-190]. The relationships obtained show the change in the electrical behavior of nanotubes from the semiconducting state to the metallic state due to the application of strain. Recently, similar effects have been obtained using complex relations and calculations, with only a few new corrections. In addition to strain, other factors such as external geometry and temperature also affect the electrical properties of nanotubes [191-193]. In fact, each multi-walled carbon nanotube has unique electrical properties. Both metallic and non-metallic behavior have been observed in these materials. On the other hand, with the change of temperature, there are some sudden changes in the conductivity of these nanotubes. Researchers have stated that the changes in the electrical conductivity of nanotubes with temperature change are beyond their imagination [194-198]. Therefore, as a general result, it can be said that the electrical properties of single-walled nanotubes depend more on chirality and the electrical properties of multi-walled nanotubes depend on the interaction of their internal layers [199-203]. Doping is another process that improves the electrical properties of carbon nanotubes. This process is amphoteric, in the sense that electron and hole doping can be done both by changing the chemical composition of the dopant and by changing the chemical potential applied to the nanotubes. With this method, the electrical conductivity of holes or electrons can be increased up to several times the intrinsic conductivity of pure materials. Doping of carbon nanotubes causes the shift of the Fermi level while keeping the band structure constant. The position of the Fermi level in undoped materials is in the middle of the bandgap width. In the case of single-walled carbon nanotubes, the position of the Fermi level is not precisely known, but it is linearly proportional to the band gap energy. But the change in the Fermi level after doping increases the population of electrons near the Fermi level and improves the conductivity [204-210].

Applications of nanoelectronics in the structure of carbon nanotubes

Carbon nanotubes are used in the structure of many nanoelectronics devices. In this section, only 2 of the most important applications are discussed: nano transistors, and p-n nanodiodes [211-213]. As an interesting example to enter the discussion, **Figure 11** shows how carbon nanotubes are placed in the structure of a nanometer transistor [2].

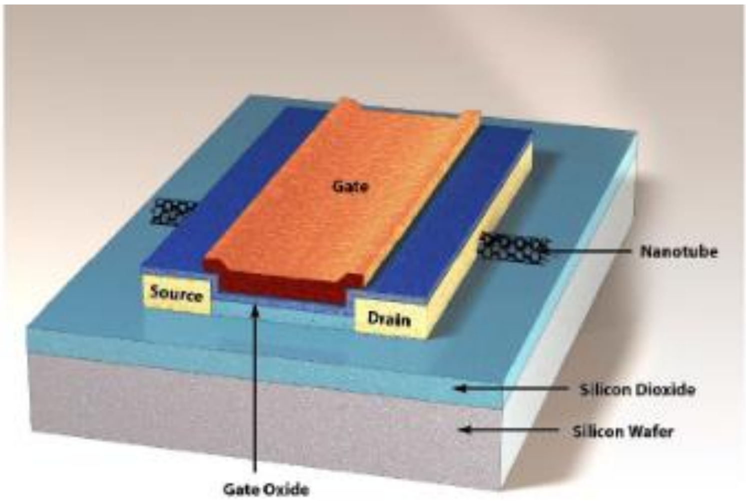


Figure 11 Application of carbon nanotubes in the construction of nanoelectronics devices [2].

Transistors

In field effect transistors based on carbon nanotubes (Nanotube Field Effect Transistors, NT-FETs), the gate is usually placed under the area where the carbon nanotube is placed. The 2 ends of the nanotube are usually connected to the source and drain metal terminals. The main method of making these transistors is that they first randomly distribute the nanotubes on the silicon substrate or place them on the substrate using an atomic force microscope. Then, with the lithography method, metal terminals are created on the nanotube [214-218]. The electrical performance of the transistors produced by this method depends on the type of nanotube and its conduction behavior (metallic or semiconducting), and the operator has no control over its final properties. Recently, researchers have stated that selective peeling of the outer layer of multi-walled nanotubes is possible in order to achieve desirable electronic properties, but this process is not yet completely reliable and may not be suitable for mass production [219-223]. The overall size of nanoelectronic devices based on these transistors is about several hundred nanometers, which is not necessarily smaller than silicon base field effect transistors [224-230]. The main goal of research in the field of field effect Nano transistors based on carbon nanotubes is to replace the conductive channel of silicon oxide base with carbon nanotubes. A basic method is to make all parts of the electronic circuit from interconnected carbon nanotubes. **Figure 12** shows the position of carbon nanotubes in field effect transistors.

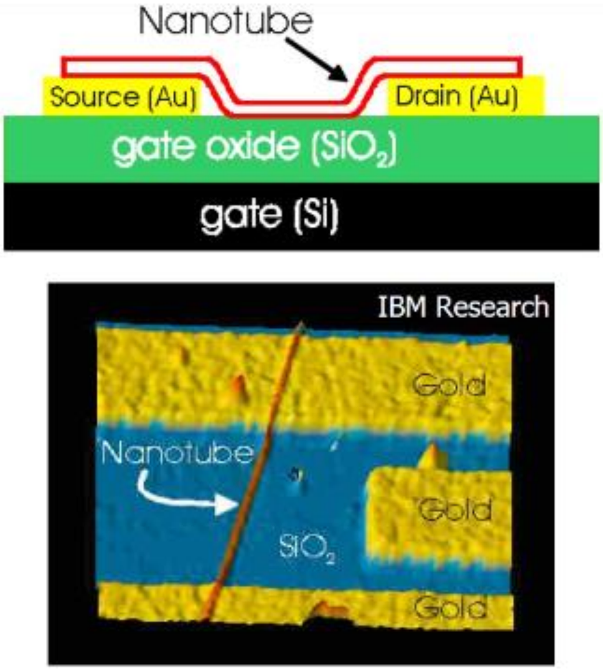


Figure 12 Schematic of the position of carbon nanotubes in field effect transistors [2].

p-n nanometer diodes

As you know, the simplest diodes are made by connecting 2 semiconductor parts, so that one part has n-doped behavior and the other has p-doped behavior. In the past, these semiconductors were made by doping materials with semiconducting behavior. This made the manufacturing process face many problems. For this reason, the efforts for field doping of semiconductor materials inside integrated circuits intensified [231-234]. One of the presented techniques was making diodes based on carbon nanotubes. Since the electrical properties of nanotubes depend on their chirality and type of doping, it is possible to make a diode in which 2 n-type and p-type semiconductor parts are summarized in a "semiconductor carbon nanotube". In other words, carbon nanotubes can be used instead of n and p type semiconductor parts, provided that charge carriers can be injected into their ends with a special technique so that the 2 halves of a nanotube can play the role of a semiconductor compared to each other. play n and p type [235-239]. p-n junctions are one of the main components in the construction of all modern semiconductor devices and are the basis of many field effect transistors and optoelectronic devices. For this reason, improving the properties of p-n junctions is essential for the development of high-efficiency electronic devices [240-243].

There are 2 general methods for doping a single carbon nanotube and converting it into an n-p junction [244-250]:

Chemical doping

Chemical doping means adding an element to the carbon nanotube during synthesis so that it can increase the concentration of electrons in one part and the concentration of holes in the other part. Recently, researchers have produced p-n junction diodes through chemical doping of individual nanotubes. But the main problem is that the electrical properties of these nanotubes show leaky behavior due to high doping and the sudden formation of 2 doped parts.

Electrostatic doping

The purpose of electrostatic doping is to apply a different gate voltage to 2 parts of a single carbon nanotube so that the band structure of one end of the nanotube changes compared to the other end, and with this, half of the nanotube acts as an n-type semiconductor and the other part plays the role of *p*-type semiconductor. Researchers have used the method of electrostatic doping of single-walled carbon nanotubes to form a p-n junction at room temperature. Electrostatic doping allows investigating almost intrinsic properties of nanotubes without creating a dopant state or changing the band structure. **Figure 13** shows a diagram of the formation of a nanometer p-n diode based on the electrostatic doping of 2 parts of a carbon nanotube. In this diode, if the gate voltage VG1 is positive and the gate voltage VG2 is negative, the nanotube itself will behave like an n-p semiconductor junction. The amount of nanotube doping can also be controlled by changing the gate voltage [256-260].

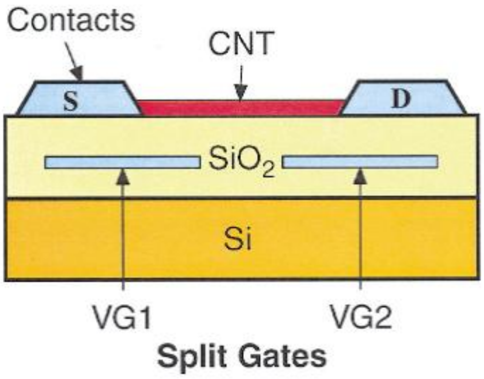


Figure 13 A diagram of the cross-section of a p-n diode based on a single-walled carbon nanotube. Gate voltage VG1 and VG2 is used for electrostatic doping of single-walled carbon nanotube. For example, if VG1< 0 and VG2 > 0, the diode is formed [2].

Electrical properties of graphene

Since graphene is a semiconductor material with 0 bandgap and its conduction and capacitance bands intersect at Dirac points (see Appendix 1), this material has very high electrical conductivity. Carbon atoms each have a total of 6 electrons, 2 of which are in the inner shell and the rest in the outer shell. The 4 electrons of the outer layer can participate in the formation of chemical bonds. But in graphene, each carbon atom is able to bond with 3 other atoms due to sp^2 hybridization. This causes an electron to remain freely in the 3rd dimension as an approximately free electron [151-153]. The electron mobility of graphene is very high even at room temperature, so that some believe that electron mobility in graphene is independent of temperature. In many laboratory researches on graphene, the main focus of studies has been on the electronic properties of this material. The most important point obtained in early research on graphene transistors is their ability to continuously change charge carriers from holes to electrons. In other words, in these transistors, both holes and electrons have the ability to carry charge and these carriers change quickly. At low temperatures and in the presence of strong magnetic fields, the very high mobility of charge carriers in graphene allows the observation of the quantum hall effect for both electrons and holes. Usually, in nanoelectronics applications, they try to change the electrical conductivity of graphene by applying gate voltage and use it in making devices such as Nano transistors and Nano sensors [261-265]. Graphene does not have a band gap, which makes the changes in its electrical resistance very small with the application of gate voltage. This is why the main limitation of graphene-based transistors is its “low on/off ratio”. The meaning of this parameter is the ratio of the intensity of the passing current in the on state to the intensity of the electric current in the off state. One of the proposed solutions to solve this problem is to carve (curve) graphene into thin ribbons (graphene nanoribbons). As graphene shrinks into thin strips, the mobility of charge carriers in the transverse direction gradually increases and leads to the creation of a forbidden band and an increase in its width. The width of the forbidden strip will be proportional to the width of the strips. Of course, this effect is more obvious in carbon nanotubes, in which the width of the forbidden band is proportional to the diameter of the tubes. The formation of the band gap and its width increase are usually observed in synthesized graphene strips and large graphene pieces patterned by lithography [266-270]. **Figure 14** shows a diagram of graphene strips resulting from unzipping of carbon nanotubes. Structural defects significantly affect the electron transport properties of graphene nanostructures. Of course, in some cases, graphene automatically fixes these defects. Defects in graphene can be divided into 3 general categories 1) vacancies, 2) impurities and 3) topological defects. In the vacancy defect, 1 or more atoms are removed from the graphene network [271-275]. In an impurity defect, a carbon atom is replaced by an atom of another element, and in a topological defect, no atom leaves the network, but the bond angles between carbon atoms change. The vacancy defect is not easily formed in graphene, so that the energy required to remove an atom from the graphene network is around 18 - 20 electron volts. The vacancy defect acts as a strong scattering center for charge transport in graphene, reduces the electron mean free path of charge carriers and disrupts the ballistic transfer of electrons in graphene. In graphene with a low or medium density of vacancy defects (0.1 - 0.01 % of the total surface), a significant reduction in electron mobility and in graphene with a high density of defects (1 % of the total surface), Anderson insulating behavior have seen. When a vacancy occurs in the graphene network, an external element can replace it and fill the void. Small atoms such as boron and nitrogen are good options for this purpose [276-280]. The presence of nitrogen atoms in vacancies leads to n-type doping in graphene. Disclination is the simplest type of topological defects, in which the hexagonal structure of carbon atoms in the graphene sheet is transformed into a 5- or 7-sided structure. Studies show that the presence of grain boundaries as another topological defect reduces electron transfer in graphene [281-285].

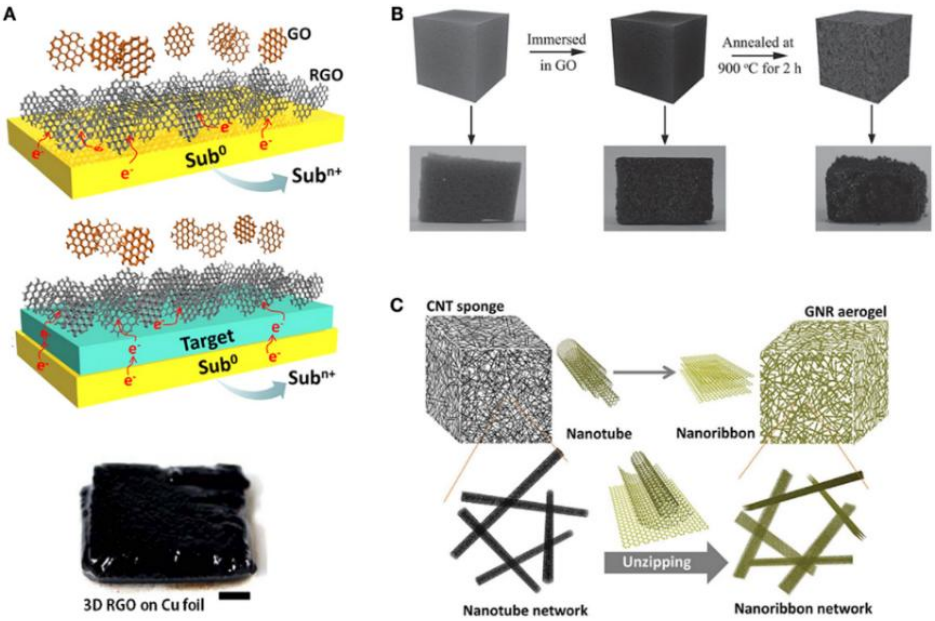


Figure14 A diagram of the process of opening carbon nanotubes and converting them into graphene strips by chemical oxidation [64].

Applications of graphene in nanoelectronics

In recent years, several nanoelectronics applications have been proposed for graphene. This section examines 2 of the most important of these applications: Nanoscale transistors, and DNA sequencing [286-290].

Nanoscale transistors

When carriers enter the graphene channel, their transport ability is controlled by the electric field applied by the gate voltage. Such transfer due to electric field is called ambipolar diffusion. Similarly, the graphene in which the bidirectional penetration of charge carriers is carried out due to the external electric field is called ambipolar graphene. Studies show that the negative bias applied to the gate increases the electron energy in the graphene conduction channel and the positive bias leads to its decrease. In 2-dimensional graphene, when the energy level of the Fermi level (EF) is lower than the energy level of the charge neutral point (ENP) (or Dirac point), holes and, if higher, electrons are transferred, because the Fermi energy of graphene is controlled by the gate voltage and as a result, the density of states (DOS) and the density of charge carriers are changed by this voltage [291-295]. This mechanism is the basis of the switching process in graphene-based field effect transistors. In simpler terms, by changing the gate voltage of the transistor, the Fermi level of graphene can be moved relative to the charge neutral point, and with this, the majority of charge carriers can be changed from electrons to holes and vice versa. This will switch the direction of the charge carriers. Unlike transistors made of conventional semiconductors with significant bandgap, graphene-based field-effect transistors do not turn off completely, even when their DOS value is 0 at the load neutral point, because the electrical conduction hysteresis with a value of about Gmin ~4e2/πh remains in them. This phenomenon is considered a key factor in the design of graphene-based nanoelectronics devices. Turning off and turning on the current in graphene base transistors is done by applying the gate voltage and their ratio is reported to be around 10 [296-300]. The exact value of this ratio depends on the quality of the graphene and the effectiveness of the gate voltage on its band structure. It should be mentioned that the digital transistors used in new applications require ratios above 10, and for this purpose, 2-dimensional graphene sheets cannot be used in the digital switch. Although the absence of a band gap in graphene has limited its use as a digital switch, but due to the excellent mobility of charge carriers, the high transverse conductivity of graphene, the low final thickness, and their chemical and physical stability, graphene is a suitable option. In analog electronics and especially, radio frequency transistors are considered. In transistors based on radio frequency, although the ability to turn off is a desirable phenomenon, it is not necessary [301-305]. **Figure 15(a)** shows a schematic of the graphene-based field effect transistor with radio frequency and **Figure 15(b)** shows the TEM image of its cross section.

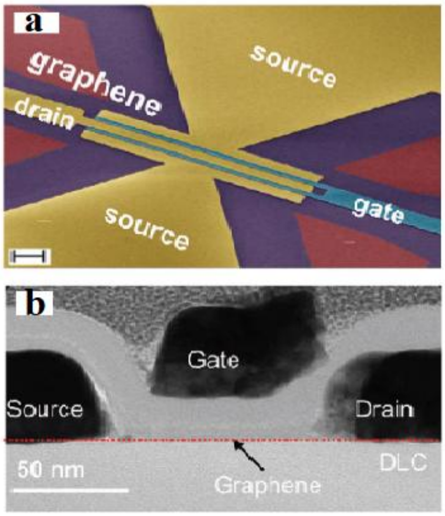


Figure 15 (a) Schematic of graphene-based field effect transistor and (b) TEM image of its cross section [64].

DNA sequencing

Large DNA molecules are composed of several branches called nucleobases. Each of these bases gives unique properties to the DNA molecule. Therefore, the order of arranging them along the molecule is very decisive. The process in which the order of bases along a DNA molecule is determined is called sequencing. DNA sequencing is a method of reading the sequence of bases within a genome and is rapidly evolving. Due to its unique structure and properties, graphene has provided attractive opportunities for the development of new sequencing technology. Sequencing is related to DNAs that pass through nanoholes, nanoslits and graphene nanoribbons and are physically adsorbed on graphene nanostructures [306-310].

DNA sequencing with graphene nanocavities is performed based on ion currents. The system used for this sequencing consists of an impermeable membrane made of graphene, which has nanometer pores and is placed between 2 electrolyte chambers. By applying a voltage difference to the 2 ends of the graphene layer containing the cavity, an ion current is created in the cavity. When the tested DNA molecule is charged with a negative charge, it can be forced to pass through the nanocavity head to tail by applying an electric field. The displacement of the DNA molecule causes the ions to be pushed out of the cavity volume and as a result, the ion current decreases temporarily [311-316]. The amount and duration of electrical current blockage provide us with information about the diameter and length of the DNA molecule, respectively. In order to be able to sequence DNA molecules with this method, it is necessary for each nucleotide to block the ion current in a different and unique way so that this blocking is proportional to the molecular size of DNA and its shape (**Figure 16**). Using graphene nanocavities for DNA sequencing is another new development in this field. Even single-layer graphene is impermeable to ions, and due to its high strength, it can form a rigid membrane against the movement of ions and facilitate the sequencing process with nanopores as an ideal atomically thin membrane [317-320]. The effective thickness of graphene in solution is only ~0.6 nm due to the damping of ion transport; While the length of the distance between 2 adjacent bases in a single-stranded DNA molecule is about 0.6 nm. Another advantage of graphene is its good electrical conductivity, which enables continuous monitoring of the intra-lamellar current through the membrane during the movement of the DNA molecule [321-323]. **Figure 17** shows a schematic of an electronic system made with graphene nanocavities for continuous monitoring of DNA by ion current measurement. It can be seen that with the movement of the DNA molecule inside the graphene cavity, the intensity of the electric current changes in steps, and each step corresponds to the placement of a base inside the cavity.

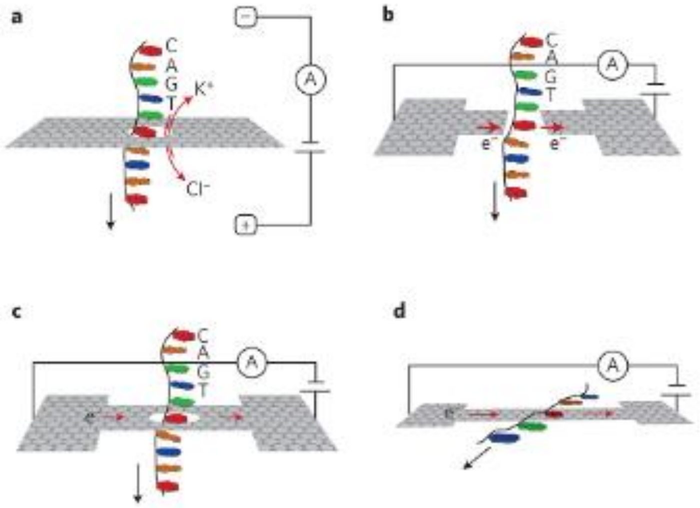


Figure 16 A diagram of DNA molecule passing through the nanometer gap of the graphene layer and changing the intensity of the passing current across the layer. The passage of DNA is done by applying a voltage difference between the 2 ends of the molecule [64].

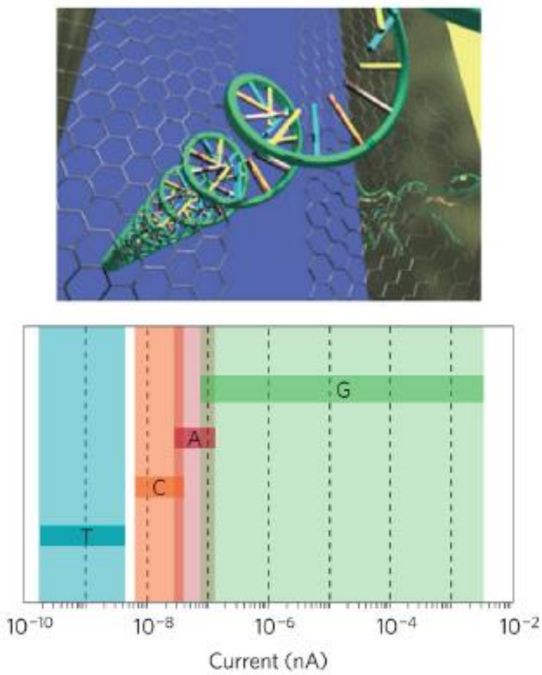


Figure 17 Schematic of the electronic system made with graphene nanoholes for DNA sequencing and changes in electric current in the graphene layer due to the passing of the DNA molecule through the width of the graphene gap [64].

Chemical composition of organic materials

According to what was said, organic substances are a family of substances that exist in nature or can be extracted from natural sources with the help of laboratory methods. Most of the substances in nature are composed of hydrogen, oxygen, nitrogen, carbon, and phosphorus. For this reason, it is expected that organic materials are also rich in the mentioned elements. In general, most known organic compounds, such as hydrocarbons, are composed of only carbon and hydrogen in different spatial arrangements [324-330]. However, in many organic substances, nitrogen and oxygen are also present. Also, some organic compounds also contain phosphorus and sulfur. The mentioned elements are the main elements in organic chemistry; However, nowadays, in order to improve some properties of organic materials, create or remove special features in them, or produce new organic compounds with unique properties, some elements of the periodic table are also added to the primary structure of organic molecules. The most important of these elements are: fluorine, sodium, copper, chlorine, and boron. In recent years, other elements such as silicon, lithium, halogens, tin, and palladium have also been added to these materials for the laboratory production of organic compounds [331-335]. **Figure 18** of the molecular structure shows examples of conventional organic structures such as butyllithium, trimethylsilyl chloride, tributyltin hydride, and halomon. Elements such as silicon, tin, copper, chlorine, and bromine are also present in the molecular structure of these organic materials. It is possible to summarize the said contents in the periodic table and create a table that includes only the elements that make up an organic substance. This table is shown in **Figure 19**. As can be seen, the most important elements in organic chemistry are carbon, hydrogen, nitrogen, and oxygen. Other elements such as halogens (F, Cl, Br, and I), p-series elements of the periodic table such as silicon, phosphorus, and sulfur, and metals such as lithium, palladium, and mercury are also of secondary importance [336-340]. Now the question must be answered, where is the exact border between organic chemistry and inorganic chemistry, and under what conditions is it considered an organic compound and in other conditions, an inorganic compound? The answer to this question becomes difficult because many mineral compounds are also composed of the same elements that are stated in the periodic table of organic substances [341-343]. To clarify the discussion, it is better to consider 2 important antiviral compounds foscarnet and tetrakis triphenyl phosphine palladium (**Figure 20**). The chemical composition of these 2 substances is CPO_5Na_3 and $C_{72}H_{60}P_4Pd$, respectively. All the elements that make up these 2 molecules are the same elements that were mentioned in organic substances. Are these compounds organic? To answer this question, we must pay attention to the chemical structure of these 2 molecules. Although the compound CPO_5Na_3 has the same chemical formula as organic matter, it does not have C-H bonds. In other words, the backbone of this large molecule is not composed of hydrogen and carbon. In contrast, the compound $C_{72}H_{60}P_4Pd$ has a large number of hydrocarbons in the form of 12-carbon benzene rings, but all these rings are attached to phosphorus atoms, and phosphorus atoms are also attached to palladium atoms. In other words, the backbone of this compound consists of C-P and P-Pb bonds and not C-H. In general, only those molecular compounds whose backbone consists of C-H bonds are called organic molecules, and in other cases, inorganic or inorganic molecules [344-348]. Therefore, the 2 mentioned compounds are considered mineral type.

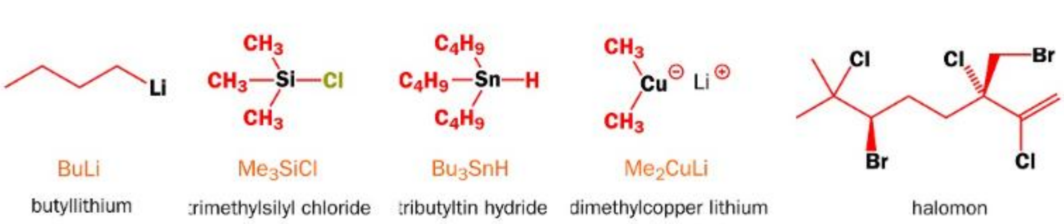


Figure 18 The molecular structure of some laboratory organic compounds that contain elements such as copper, silicon, and lithium in their chemical composition [59].

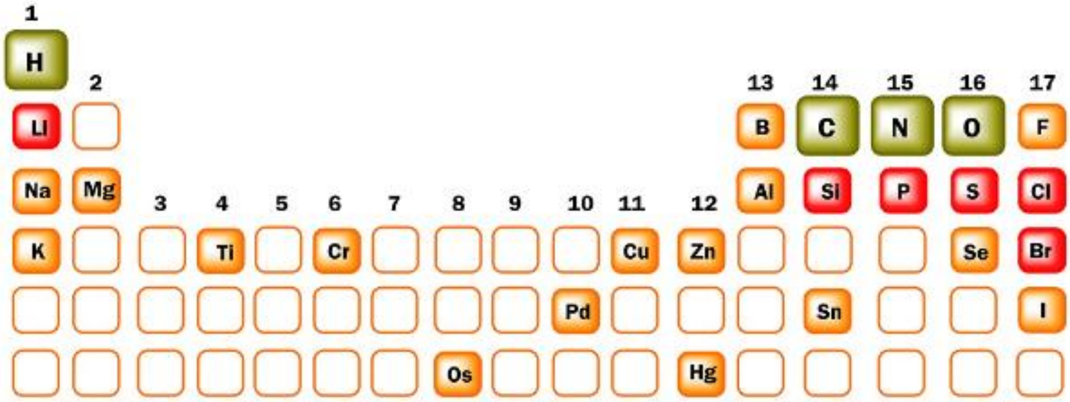


Figure 19 Periodic table of organic substances [59].

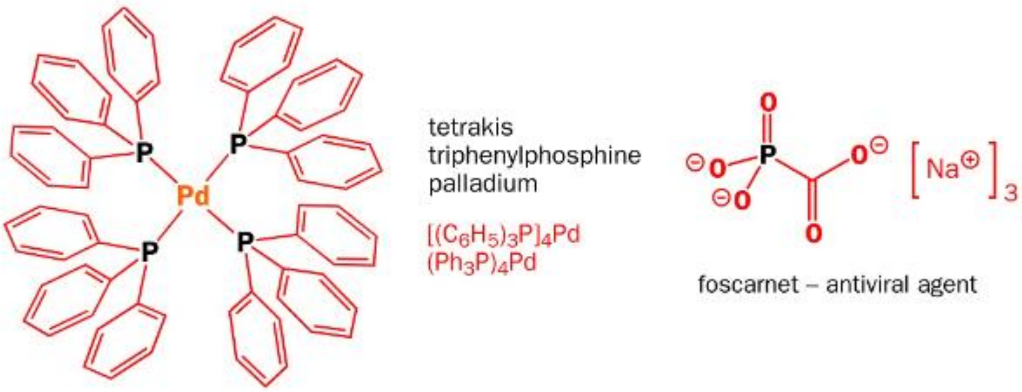
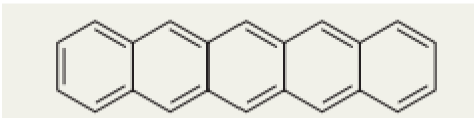
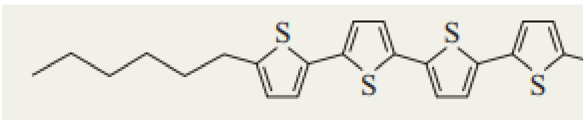
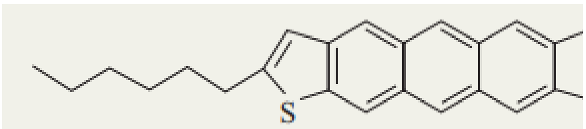


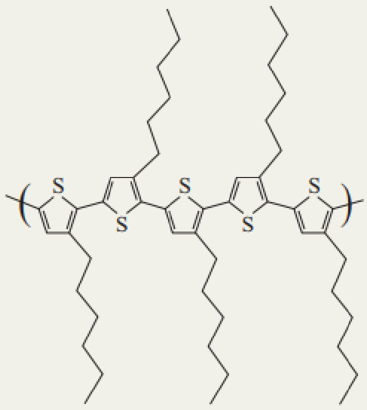
Figure 20 Two examples of inorganic compounds used in medical applications as antivirals with similar chemical composition to organic substances [59].

Advantages of organic materials in nanoelectronics

In the last 50 years, the field of microelectronics and nanoelectronics has used inorganic semiconductors such as silicon and gallium arsenide, insulating materials such as silicon oxide, and metals such as copper and aluminum to make electronic devices. In the last decade, efforts have been made to use organic materials in the manufacture of nanoelectronics devices, and research in this field is focused on improving the semiconducting, conductivity, and optical emission properties of organic materials (polymers and oligomers) and hybrid materials (organic-inorganic composites) with the development new synthesis methods and molecular self-assembly techniques are focused on [349-353]. The main goal of developing organic nanoelectronics has been to improve the efficiency of electronic devices and the possibility of producing a wide range of new materials such as plastics at lower temperatures and at a lower cost. The aforementioned goals are considered to be one of the advantages or research priorities of the field of organic nanoelectronics. It should be noted that organic materials were also used in the silicon-based electronics industry, but they were not considered to play a key role. For example, most organic materials were used either as sacrificial patterns or photoresists or as passive insulators [354-360]. Later, with the development of a wide range of organic materials with light emitting properties and relative conductivity, it became possible to use these materials as the main components of nanoelectronics devices. In addition to the mentioned advantages, one of the main weaknesses of organic materials in electronic fields is the low mobility of charge carriers and the relatively low efficiency of these materials compared to silicon-based devices [361-365]. **Table 2** shows the chemical structure and mobility of charge carriers in some organic materials compared to inorganic silicon materials. As can be seen, the mobility of charge carriers in semiconducting organic materials is at best similar to that of amorphous silicon and far from that of crystalline silicon. As a practical example, pentacene thin films are used today to make thin film transistors used in liquid crystal displays. Most of the materials mentioned in **Table 2** work at very high voltages. Therefore, it is necessary to think of measures to use these materials at lower voltages. One of the proposed solutions is the development of hybrid systems of organic materials and minerals. Most organic semi-conducting materials are p-type and transport holes rather than electrons. However, n-type organic materials are also very important for making p-n junctions and logic circuits. More studies are needed to increase the mobility of charge carriers in organic nanoelectronics materials so that the electrical efficiency of organic-based devices can be improved by better understanding the electron injection, the nature of bonding of metal electrodes to organic materials, transport of charge carriers, surface modification of layers, and molecular self-assembly and increased it to the limit of polycrystalline silicon efficiency [366-370]. If humanity can achieve this goal in recent decades, we will witness the development of very cheap and efficient nanoelectronics devices and logical circuits based on organic materials [371-373]. As a practical example of the role of organic materials in nanoelectronics devices, consider **Figure 21**. This figure shows a schematic of an organic thin-film light-emitting diode, which consists of a metal anode and cathode, and 2 separate layers of 2 organic polymers are placed between them. By applying an external voltage difference between the 2 electrode layers, a flow of excited electrons is generated in the Alq3 organic layer as an n-type semiconductor. Similarly, an avalanche of excited holes is formed in the organic layer of NPB as a p-type semiconductor. It is said that Alq3 organic layer plays the role of electron transporter and NPB organic layer plays the role of hole transporter. The generated charge carriers can move towards the interface of 2 organic layers due to the external electric field, and by recombining these 2 types of charge carriers, light with a specific wavelength is emitted from the diode. Many efforts have been made to improve the light emission efficiency of organic light emitting diodes (OLEDs) [374-380]. **Figure 22** shows this process. As can be seen, the light emitting efficiency of OLEDs devices has grown significantly in the last 15 years, so that these devices can now compete with silicon light emitting diodes. It should be noted that today this efficiency has reached such a level that the intensity of light received from an organic diode can be much higher than incandescent bulbs.

Table 2 Chemical structure of insulating materials and organic and silicon semiconductors and the mobility of charge carriers in them [59].

Semiconductor	**Representative chemical structure**	**Mobility ($cm^2V^{-1}s^{-1}$)**
Silicon	Silicon crystal	300 - 900
Silicon	Polysilicon	50 - 100
Silicon	Amorphous silicon	~1
Pentacene		~1
a,ω-dihexylsexithiophene		10^{-1}
a,ω-dihexylanthradithiophene		10^{-1}

Semiconductor	Representative chemical structure	Mobility ($cm^2V^{-1}s^{-1}$)
Regioregular poly(3-hexylthiophene)		10^{-1}
Organic-inorganic hybrid	Phenethylamine-tin iodide	~1

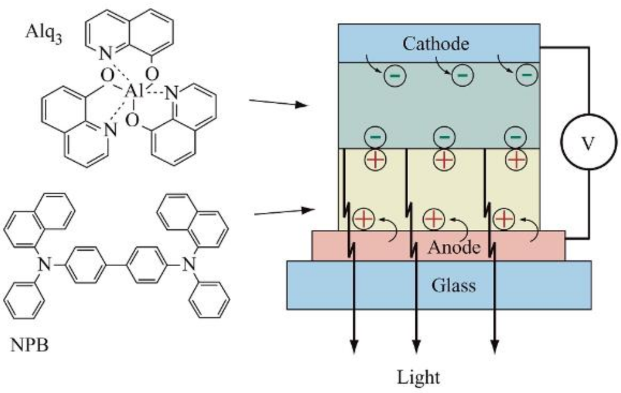


Figure 21 Schematic of a light emitting diode based on organic materials. In this diode, 2 metal electrodes anode and cathode act as voltage application terminals, and 2 organic layers Alq_3 and NPB act as electron and hole transporters, respectively. Light is emitted from the recombination of electron and hole at the interface of 2 organic layers [59].

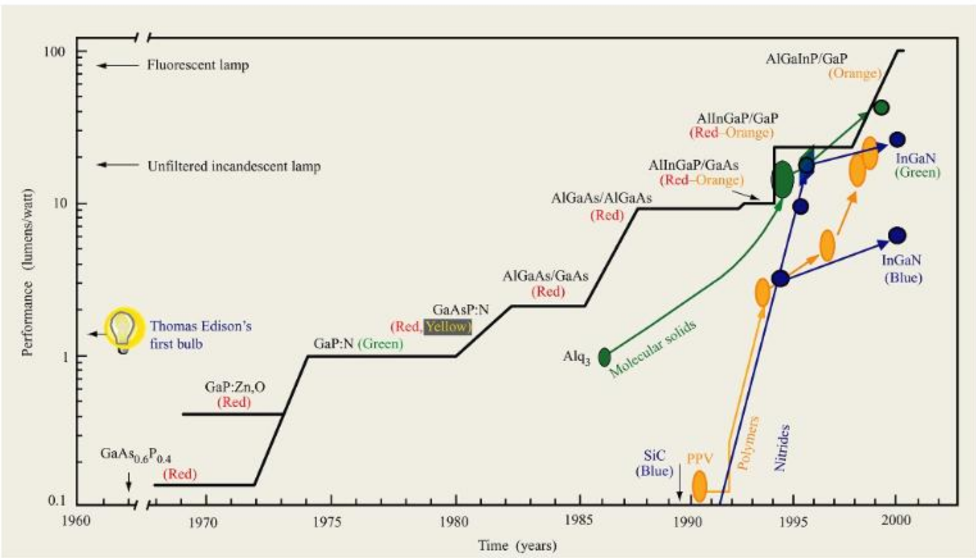


Figure 22 The process of improving the efficiency of organic and inorganic light emitting diodes [65].

Types of organic materials used in organic nanoelectronics

Although, with the development of the field of organic nanoelectronics, a new range of organic materials may be used due to their unique electronic properties, 4 general categories of organic materials have been used in electronic applications so far: (a) charge-transfer organic complexes; (b) conductive polymers; and (c) conductive gels; and (d) dielectric polymers [205].

Organic complexes of electric charge transfer

The idea of developing organic charge transfer complexes (organic charge transfer complexes) originates from the fact that if it is possible to create 2 areas inside an organic system, one of which wants to receive and the other wants to give electrons, the free electrons of the material, will have the possibility to easily move between donor and acceptor centers and create significant conductivity inside the material [381-383]. Accordingly, charge transfer organic complexes are those organic substances that have a large number of electron donor and acceptor centers in its volume and the conditions for electron exchange between these centers are available. In other words, these materials are in the form of molecules in their structure, there are centers with 2 different band structures, and one of these centers has a tendency to donate electrons and the other part is interested in receiving electrons (electron affinity) [384-388]. In this way, the electron can move along the molecular chain. **Figure 23** shows the strip structure of 2 neighboring donor and recipient regions for 2 different types of distribution of these centers. As can be seen, if a substance wants to play the role of an electron donor, its valence and conduction bands should be at higher energy levels compared to its electron pair band structure. In this case, unconsciously, the width of the forbidden band is reduced from Pintra to Pinter and the transfer of electrons is facilitated. In practice, organic charge transfer complexes can be synthesized in 2 ways: (a) adding organic or inorganic substances to an organic substance; and (b) synthesis or layering of 2 organic materials in the form of parallel sheets. In the 1st case, an organic material with high electron-affinity organic material is composited with another organic or inorganic material with low electron-affinity organic material. In this case, one material plays the role of electron acceptor and the other plays the role of electron donor [389-394]. The important point is that the 3-dimensional structure of these composites should be very uniform and the aforementioned centers should be homogeneously distributed throughout the material. These structures are also called mixed stack structures. In the 2nd case, 2 organic substances with different electron-withdrawing power are layered on top of each other in the form of layered arrays. These structures are called segregated stack structures or organic charge transfer salts. **Figure 23** shows a picture of these 2 structures. **Figure 24** also shows the optical image of the general microstructures of these materials. As can be seen, when anthracene material as an electron donor and PMDA (pyromellitic dianhydride) material as an electron acceptor are mixed together to form a charge transfer organic complex, the color of these materials compared to the original state is full length. It changes. This color change shows that the band structure of these materials has been completely changed after mixing, and in general, the width of the forbidden band of electrons in this structure has been significantly reduced. Color change compared to the initial state is one of the characteristic features of charge transfer organic complexes [395-400].

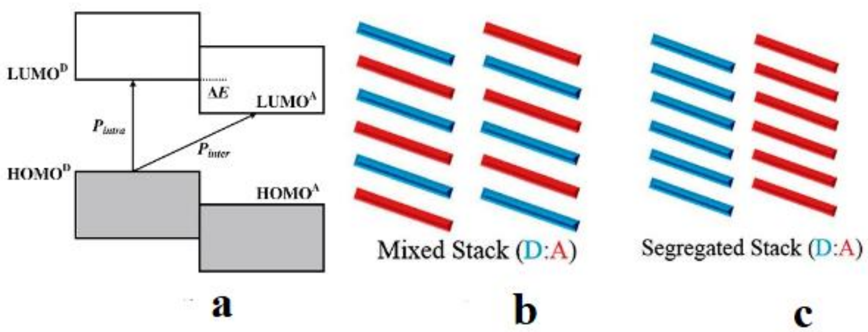


Figure 23 (a) The strip structure of the interface of 2 polymer components A and D in charge transfer organic complexes, (b) and (c) schematics of their mixed and layered structures [65].

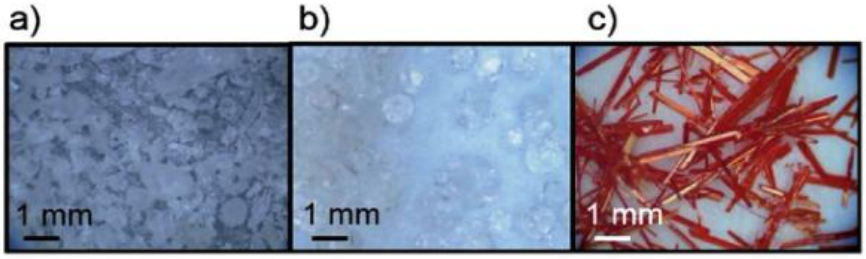


Figure 24 Light microscope images of anthracene material as an electron donor (a), PMDA material as an electron acceptor (b), and a composite of 2 organic materials as an organic charge transfer complex (c) [65].

Conductive or conjugated polymers with π bonds

Most polymers have dielectric behavior and are often used as insulators in electronic applications. In order to be able to use them instead of silicon-based semiconductor materials or conductive metals, the conductivity of polymers should be increased. In the past, this was done by adding particles of conductive materials to organic polymers, but the increase in conductivity was not enough to meet the needs of the electronics field. Therefore, the idea of developing intrinsically conductive polymers was proposed [401-405]. Observations showed that there is a special category of polymers known as "conductive or conjugated polymers with π bonds" that exhibit semiconducting behavior. In other words, the conductivity of these materials is strongly dependent on temperature and increases with increasing temperature. But what is the reason for this semiconducting behavior in conducting polymers? In fact, conducting polymers have consecutive single and double bonds. Double bonds have bonding electrons in π orbitals, and they can move out of bonding orbitals and climb into anti-bonding *π orbitals due to relatively small thermal or electrical stimulation [406-410]. This means that the electrons of the double bond can escape from the bonds of the atoms due to thermal or electrical stimulation and flow freely along the polymer chain. If antibonding electrons flow along the molecular chain, single bonds become double bonds and double bonds become single bonds, and thus a wave called a soliton wave is created along the chain. **Figure 25** shows the molecular structure of polyacetylene conjugated polymer in the state of trans isomer (Trans-polyacetylene or trans-(CH)x). The bandgap width of this polymer depends on the length of single and double carbon-carbon bonds [411-415]. As the lengths of single and double bonds are closer to each other, the conductive behavior of conjugated polymer tends towards the behavior of metals. In general, the conductivity of conjugated organic polymers is similar to the electrical conductivity of intrinsic semiconductor materials, and the reason for that is the low concentration of free charge carriers. Therefore, it is better to increase the number of charge carriers in conducting polymers by doping a suitable additive, similar to non-intrinsic semiconductors, and create a series of additional allowed levels in the vicinity of the conduction and capacitance bands. In fact, adding the dopant element to the molecular structure of conjugated polymers causes the injection of a large group of electrons and holes into the material. These added charge carriers, as a result of a series of energetic interactions, cause the formation of quasi-particles called solitons and increase the electrical conductivity of these materials [416-421]. For example, today dopants such as AsF2, I2 and Br2 are used to increase the electrical conductivity of trans-polystyrene. Studies show that the addition of such dopants can even increase the electrical conductivity of conductive polymers up to a billion times and produce a conductive behavior similar to that of metals. In general, the factors affecting the conductivity of conductive polymers are: (a) mobility of electric charge carriers; (b) density of charge carriers; (c) type of doped ions; (d) Dopant concentration; and (e) temperature [422-426].

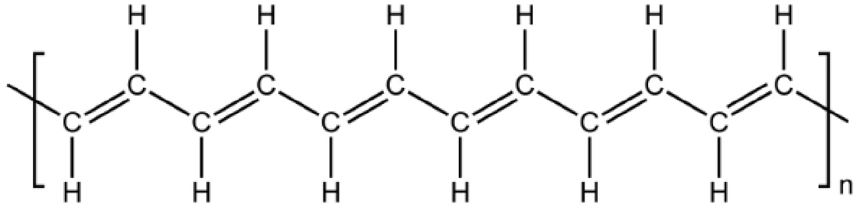


Figure 25 Molecular structure of polyethylene conjugated polymer in trans isomer state [59].

Conductive or conjugated gels with π bonds

The performance and efficiency of nanoelectronics devices based on "conjugated polymers with π bonds" depends on the degree of crystallinity of these materials in the process of making thin films and their quality. In general, there are several basic challenges in the field of using conductive polymers to make electronic devices, the most important of which are the following [426-428]:

1) Controlling the morphology and degree of crystallinity of conducting polymers is very difficult and strongly depends on the heating rate and microstructural parameters of these materials.

2) It is very difficult to produce conductive polymers with very high purity in the synthesis process.

3) The solubility of conjugated polymers in aqueous solutions is relatively low.

To get rid of the mentioned challenges, a special category of organic materials called "supramolecular polymers" of conjugated molecules with π bonds or "conductive gels (π-gels)" has been developed. In fact, the molecular structure of conductive gels consists of regular arrays of conjugated molecules with different shapes and dimensions. The most important features of conductive gels are the possibility of achieving photoluminescence properties and easy control of the mobility of charge carriers and their electrical conductivity. Three points about conductive gels and their properties are very important: First, the bonding structure of the molecules that make up conductive gels is similar to conjugated polymers with π bonds. In other words, the molecules forming a conductive gel have successive single and double bonds, and the electron current flows through the resonance of the bonds along the molecular chain. Second, the molecules that make up conductive gel often have molecular self-assembly behavior. In other words, repulsive or attractive forces between molecular units lead to a certain arrangement of molecules next to each other. This self-assembly property leads to special electrical behavior in these materials. The 3rd point is that in many conventional conductive gels, the impact of a light beam can lead to the excitation of π orbital electrons in this. In other words, a part of the wavelength of the incident light may be absorbed by the structure of the conductive gels and we will see the color of the gel change due to the incident light. This photoluminescence property can be used in light emitting diodes (LEDs) [220].

Dielectric polymers

Most polymers are insulators and often do not conduct electricity. The most common application of these materials in nanoelectronics is their use as an insulating layer in the gate terminal of organic field effect transistors. **Figure 26** shows you the general structure of these transistors. To build this structure, 3 insulating layers have been used in the gate terminal: aluminum oxide layer (Al_2O_3), thin layer of HfO_2, and an amorphous polymer layer (amorphous fluoro-polymer layer or CYTOP). Another nanoelectronics application of insulating polymers is their use as a separator/isolator layer in electrical energy storage capacitors [429-432]. The most common insulating polymers are polymethylmethacrylate, polyvinyl phenol, polystyrene, polyvinyl alcohol, polyamides, and parylene. **Figure 27** shows examples of molecular structures of insulating polymers. Often, 2 layers of polymer insulation are used in nanoelectronics devices. This work has 2 main reasons: (a) to ensure the sufficient strength and insulation capacity of this layer; and (b) a preferred interface to grow an organic semiconductor layer on this layer. It should be noted that the degree of polarization, viscosity, hydrophobicity, and surface roughness of the dielectric polymer layers strongly affects the growth of the organic semiconductor layer and its quality [433-435]. One of the most common methods of layering organic semiconductor on insulating polymer in organic field effect transistors is precision lithography [59].

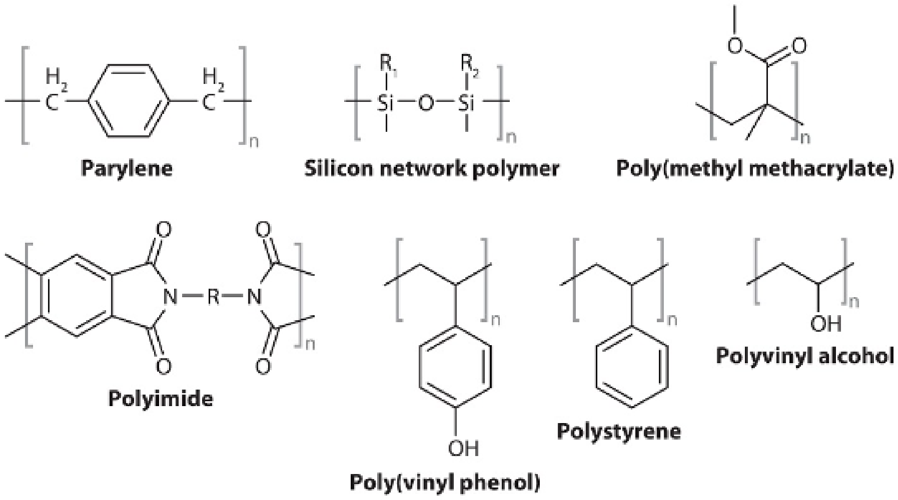


Figure 26 A diagram of the general structure of organic field effect transistors in which 3 layers of aluminum oxide, hafnium oxide, and insulating amorphous polymer are used as the insulating layer in the gate terminal [59].

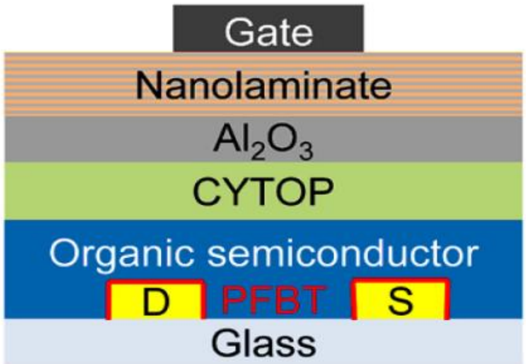


Figure 27 Molecular structure of several dielectric polymers [2].

Classification in the field of nanoelectronics

There is not much consensus regarding the division of different fields of nanoelectronics. The reason for this challenge is the interdisciplinary nature of this field, its rapid and leapfrog development, and the provision of classifications based on the specialized backgrounds of researchers. For example, electronic engineers tend to divide this field based on the type of electronic equipment [222]. Chemistry researchers based on the chemical methods of construction, physics researchers based on the theoretical nature of the topics, and material engineers based on the materials used and the final applications of the manufactured equipment, provide their classifications. It is the lack of this single division that has caused the beginner readers to get trapped in a sea of apparently unrelated topics after referring to the scientific sources of this field. In general, there are currently several approaches for dividing the different branches of nanoelectronics [223].

Classification based on electronic devices

Based on this, nanoelectronics includes methods that lead to the production of electronic units on a nanometer scale. These units include logic circuits, transistors, diodes, molecular memories, etc [224].

Classification based on the dimensions and layout of the used electronic components

In this type of division, the type of material used, the application, and the final performance of the desired material are not considered, and only the number, dimensions, and arrangement of the components are discussed. Based on this, nanoelectronics includes nanoelectronics of single-unit and multi-unit systems [436-438]. For example, if a single enzyme or molecule is used in the construction of a Nano sensor, this sensor belongs to the domain of single-unit nanoelectronics, and if it is made of a nanometer layer or a nanometer array of electronic units such as organic molecules, it belongs to the domain of multi-unit nanoelectronics. Monomolecular and multimolecular organic compounds are another example of these devices [439-443].

Classification based on the type of electronic materials used

The basis of this division is the chemistry of the materials used. In this respect, materials are divided into 2 categories, organic and inorganic, and develop 2 large fields of organic and inorganic nanoelectronics. Inorganic nanoelectronics includes all devices and technologies in which the main base of electronic products is not organic matter. For example, C60-based fullerene junctions can be mentioned. It should be noted that most researchers do not use the word "inorganic" and use the term organic nanoelectronics whenever it is necessary to emphasize the organic property of the system. Therefore, as long as the word "organic" is not used for a device, it means the field of inorganic nanoelectronics [444-450].

Classification based on end uses

In this division, the basis of work is the type and type of application of the produced equipment. Application means biological and non-biological applications. On this basis, nanoelectronics is divided into 2 major sub-branches of biological and non-biological nanoelectronics. Similar to organic nanoelectronics, wherever it is necessary to emphasize the biological nature of the system, the term biological nanoelectronics is used. Also, as long as the word "biological" is not used for a device, it means the field of non-biological nanoelectronics [229].

Multi-approach classifications

In this type of classifications, several mentioned categories are used simultaneously. For example, in some sources, terms such as biomolecular nanoelectronics or bioorganic nanoelectronics are also used. The reason for this approach is the development of emerging tools and the lack of clear boundaries between different categories [230]. In some sources, non-molecular materials with dimensions below 100 nm are referred to as molecules, and on this basis, graphene-based Nano sensors or carbon nanotubes belong to the field of molecular nanoelectronics. In other words, carbon nanotubes, nanoribbons and graphene are also considered inorganic molecules. Although the classifications in the field of nanoelectronics are very diverse and trying to provide a common classification seems impossible, the type of classifications has no effect on the manufactured devices [231]. For example, whether graphene is considered as a molecular component or an organic or inorganic nanometer unit will not make a difference in the discussions of graphene-based nano sensors. What we use in the discussions related to nanoelectronics in the articles of the education site is a newer category in which all the aforementioned categories are taken into account in some way. This category is given in **Figure 28**. As can be seen, this division is based both on the type and chemistry of the substance, and on its biological and non-biological application, and there is no requirement to use the word molecule for non-molecular nanoscale components [232-236].

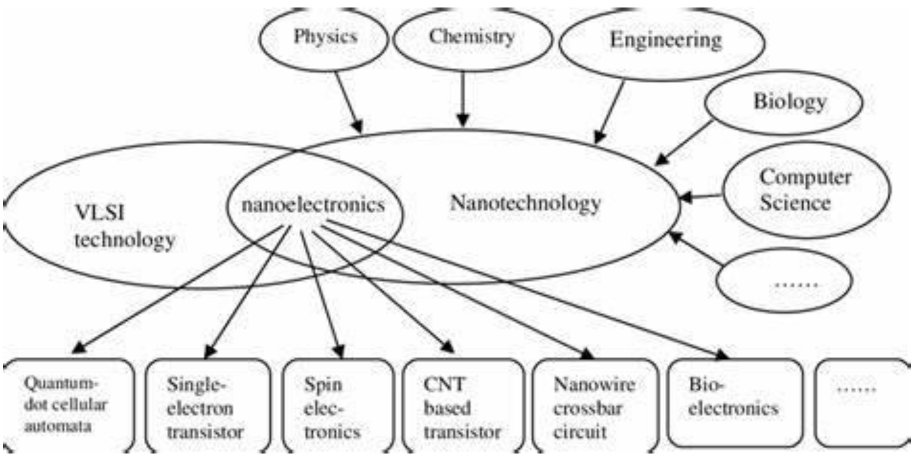


Figure28 Classification in the field of nanoelectronics [66].

Electro biochemical principles governing nanoelectronics

Perhaps the most key question that can be raised regarding nanoelectronics topics is how molecular units and nanometer components can be used as the main components of nanoelectronics components. In other words, what is the unique feature of these nanoscale materials that makes their use in electrical processes possible. Basically, the main element in nanoelectronics equipment is the flow of electric current, and in order for these materials to play a role in an electric circuit, they must have the ability to pass current or not pass current in certain conditions. Therefore, what is studied in nanoelectronics physics is the electron transfer mechanisms in nanoscale materials, their kinetics and dynamics, and finally the effect of various material parameters, design and intrinsic of the systems on the electronic behavior of the used components [237-239]. Electron transfer mechanisms will be the main topic of some articles that will be presented in other sections. In general, electron transfer mechanisms in nanoelectronics materials include coherent and incoherent tunneling, electron jumping, Poole-Frenkel effect, and thermionic/Schottky emission.), and Fuller-Noderheim mechanism (donor-bridge-acceptor molecules). The study of electron transfer in nanoelectronics materials is very important from the aspect that in these materials due to the nanometer size of the electronic components, a certain quantum confinement (quantum confinement) for the flow of electric current is created. In other words, according to the classical principles of electricity, the flow of electrons in a semiconductor or metal wire follows Ohm’s law, so that its electrical resistance increases as the length of the wire increases. While this law is not true for electrical conductivity in nanometer units. The reason for this is the existence of quantum limitations in the transfer of electrons between energy levels in nanometer units and the so-called localization of energy levels in them [240]. This different behavior has opened the way for the design of various nanoelectronics devices. For example, by applying an electromagnetic field or applying a voltage, the behavior of a nanometer unit or molecule can be changed from a metallic state to a semi-conducting or non-conducting state. More importantly, it is possible to manage and control the path of electron transfer in nanoelectronics devices by changing the electrical forces on the nanoscale units. For example, it is possible to create conditions where the movement of electrons from a nanometer semi-conducting layer into the metal is carried out with high kinetics. Also, by changing the voltage applied to the connection, the electron transfer can be stopped or its intensity can be controlled as desired [241-242]. Another way to manage electron transfer in nanoelectronics systems is to add dopant to components and change the band structure of the system. In general, it can be said that molecules and nanoscale units, under certain conditions, can show one of the behaviors of conductivity, non-conductivity and semi-conductivity. For example, in molecules that have 3 electron donor, bridge and acceptor parts in their electron levels, it is possible to transfer electrons and the molecular system will be conductive or semi-conductive. In molecular joints based on rotaxane molecule, it has been observed that the injection of electric charge or the placement of the joint in a strong electric field causes the isomerization process or change in the geometric shape of this molecule and finally the band structure of the joint is changed. This is why the phenomenon of isomerization or changing the spatial arrangement of molecules can be used in the design of devices such as molecular switches. As a 2nd example, we can refer to the behavior of the biological molecule DNA. It has been observed that the electron mutation along DNA depends on the sequence of its nucleobases. For this reason, depending on the conditions, DNA molecules can show a wide range of electrical behaviors (insulating, semiconducting, metallic and even superconducting). For example, by changing the sequence of base pairs in DNA, the electrical conductivity of DNA molecules can be completely removed [243-246]. **Figure 29** shows the single-stranded DNA molecule passing through the nanopore of the graphene layer. As can be seen, when the guanine base passes through the nanocavity, the electric current passing through the graphene changes.

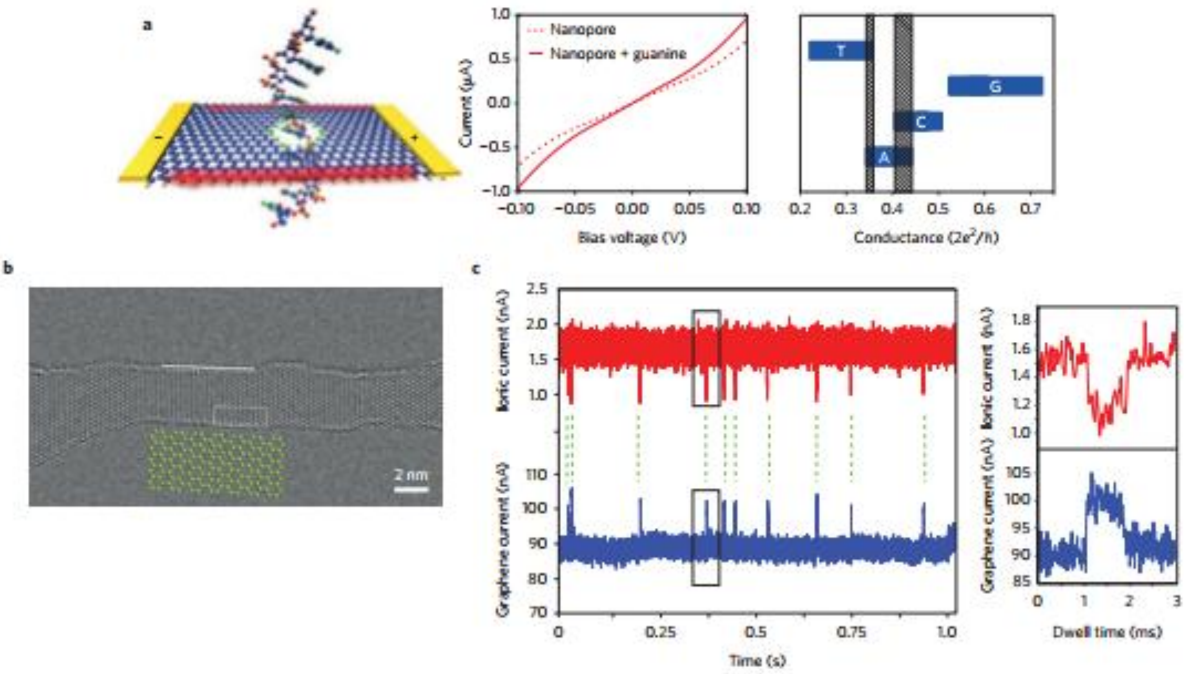


Figure29 (a) Schematic of the single-stranded DNA molecule passing through the nanopore created in the graphene layer; and (b) the current-voltage diagram related to the graphene layer in the state without DNA and in the state where the DNA molecule passes through the nanocavity [66].

The main sub-branches in the field of nanoelectronics

The successes achieved in the field of nanoelectronics have led to the development of this nascent scientific branch and its entry into other fields of application, so that today it is rare to find an application in which nanoelectronics is not used. Nanotechnology, biotechnology and defense industries are among the most important fields of nanoelectronics applications. So far, a comprehensive classification for nanoelectronics has not been provided, and some authorities have categorized the sub-branches of nanoelectronics according to their personal approach. However, this new branch of science can be studied in the following several areas [247-250]:

1) Nano sensors
2) Lab on a chip
3) Artificial organs
4) Bionics and biomimetic
5) Imaging
6) Integrated circuits
7) Molecular nanoelectronics

There may be important nanoelectronics applications that do not fit into any of these branches. Devices may also be developed that belong to 2 or more sub-disciplines, depending on their application, the type of technology used to manufacture them, or the scientific/technical basis governing them. This issue shows the need to develop a more comprehensive classification for nanoelectronics subfields [250].

Nano sensors

Perhaps, Nano sensors can be considered the most important and common sub-branch of nanoelectronics, because in most industries, including military, medical, agricultural, and food industries, there is a need to measure some useful or disturbing factors in the desired environments. For example, diabetic patients need to measure blood sugar or the amount of glucose in the blood in order to regulate it. In agricultural industries, there is a need to measure the amount of agricultural toxins in the final products. In the food industry, it is necessary to measure the amount of environmental pollutants or the amount of toxins in food with very high accuracy. The question may arise that such measurements can be done in specialized laboratories with different methods; So, what are the advantages of Nano sensors? The answer is that in many applications we are looking for instant and momentary measurement of the desired factors with the lowest cost. For example, diabetic patients can measure their blood sugar without visiting a doctor. Another example is the control of some standards in materials that enter countries through customs. Therefore, the main advantage of Nano sensors; The desired factors are measured in a short period of time and in the field with the lowest cost. A Nano sensor usually consists of several main components: 1) receiving part or detector component; 2) converter; and 3) display. The factor to be measured is called analyte. Most analytes have low concentrations. The receiving part is selected and designed to react only to a specific analyte. Therefore, one sensor should not be expected to measure both gas leakage in a residential complex and blood glucose. In some sensors, the receiving part reacts with the analyte, and as a result of this reaction, the behavior of the electrical conductivity of the receiving part changes. These changes are received by the transducer and finally converted into measurable data by the display. The signal created in the transducer will be proportional to the concentration of the analyte. Therefore, depending on the type of receiving part, the type of reaction between the detector component and the analyte, the mechanism of converting changes into output signals, and the desired application, Nano sensors are classified into different types. For example, **Figure 30** shows the Nano sensor used to measure glucose concentration in the blood of diabetic patients. Glucose, as the common fuel of body cells, is oxidized by the enzyme glucose oxidase (GOx). This reaction changes the potential of the medium in proportion to the initial concentration of glucose. As a result of this reaction, a stream of electrons enters the detector component and is received by the transducer, and converted into output data. Observations show that by using surface nanocomposites or using some nanoparticles on the receiving part, the reaction of the analyte with the detector component or the electron transfer in the interface can be accelerated, thereby increasing the detection speed of the analyte. Today, researches in the field of Nano sensors are directed towards the development of new and efficient materials for reacting with different analytes and designing systems to receive information quickly and accurately and convert them into output signals [52].

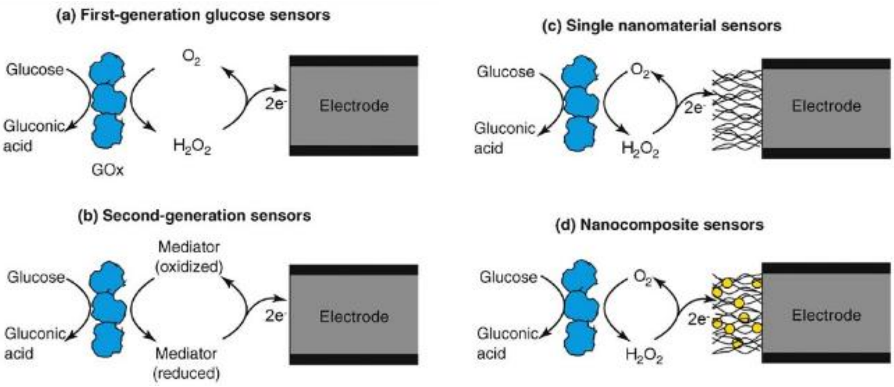


Figure30 A diagram of blood glucose detection by a Nano sensor: (a) Glucose interacts with the metal electrode, causing electron exchange with it; (b) the enzyme glucose oxidase (GOx) is used to accelerate the reaction between glucose and the electrode; (c) nanometer arrays are used on the metal electrode, which accelerates both the reaction between glucose and the electrode, and the electron transfer between them, and (d) the use of a surface nanocomposite on the electrode, which accelerates the desired reaction and electron transfer between becomes analyte and electrode [52].

Bionics

Bionics is one of the branches of science that has received attention due to the intense interest of scientists and engineers in studying nature and its structures. Inspired by nature and its laws or by direct imitation of nature, this science helps to build and increase productivity in various engineering sciences such as electronics and nanoelectronics, computer, mechanics, architecture and management sciences and biotechnology. In fact, bionic science is a set of sciences in which living organisms and the laws of nature are studied with the aim of creating and developing various technologies in various sciences today [251]. Bionics can be considered as the art of using knowledge obtained from nature in solving technical issues and problems in various sciences. In bionic science, devices are made that work based on the materials or mechanisms of systems in nature. Meanwhile, scientists are looking to invent and develop different technologies, methods and mechanisms. Therefore, bionics seeks to create a link and a bridge between knowledge derived from nature and different technologies. This link is not only copying and imitation, but also includes the inspiration of mechanisms and methods. Inspiration from living systems to investigate and build machines has been one of the 1st applications of bionic science [252]. The 1st example of this creativity can be considered a flying car that was created by the famous painter Leonardo da Vinci and was inspired by the body structure of a bat. He argued that the membrane-like skin that covers the bat's wings and does not allow air to pass through it gives the bat its ability to fly. Bionic science can be divided based on the mechanism or based on its application. From the terminological point of view, bionics means "biological" or knowing the structures and structures in nature and using them in different sciences. This word is composed of 2 parts bio (bio) meaning life and the suffix ic (ic) meaning similarity [253]. "Biomimetics" is another term that is commonly used in the field of bionics, and some consider it synonymous with the word bionic. This word consists of 2 parts bio and mimetic (derived from the word imitation) and its meaning is imitation of life (nature). In fact, biomimetic is a branch of bionics that only imitates living and non-living parts of nature. "Bioinformatics" is another science that is studied along with bionics as one of the branches of bio-nanoelectronics science. According to biological data, this science provides very valuable algorithms for the development of engineering and medical systems. This science consists of other parts such as the development of software for communication between different biological data and their management. That part of bioinformatics, which is directly related to nature and produces and develops algorithms derived from it, is considered a branch of bionic science [254].

Types of bionic classifications

Classification based on mechanism

Process bionics

This branch of bionic science deals with the construction and design of various technologies inspired by nature, its processes and laws. Among the sub-branches of this field, we can mention architectural bionics, bionic sensors and bionic energy [255].

Structural bionics

This branch of bionic science deals with the development of various technologies and the construction of parts such as robots, implants, and nanoelectronics equipment based on materials found in nature [256].

Information bionics

In this branch of bionics, algorithms and natural data are studied to be used in the design and construction of various electrical and computer equipment. Firefly algorithm, honey bee algorithm, ant algorithm and genetic algorithm are among the algorithms that have been developed in this field [257]. **Figure 31** introduces some active areas of the bionic field and its subfields.

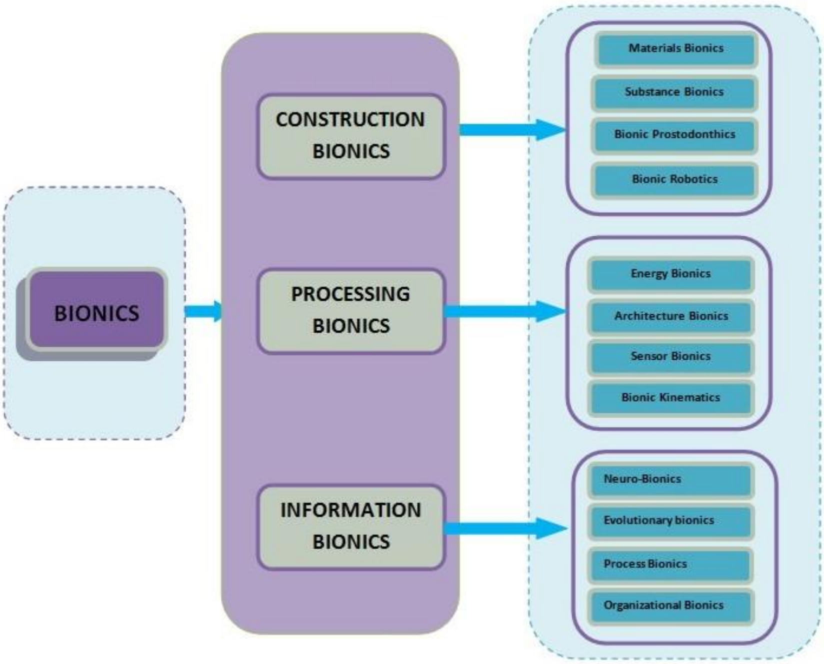


Figure 31 The active areas of bionic science include process bionics, structural bionics, and informational bionics [60].

Classification based on application

Bionic architecture

Today, architecture is one of the fields that uses bionics to advance its goals. Considering today's human population, the lack of natural resources, the increase in the level of people's expectations and the emergence of new technologies, architectural science engineers seek to use the laws of nature to make today's buildings more efficient. Bionic architecture offers a promising way to solve architectural problems inspired by living organisms and the architecture of nature's structures so that today's buildings make better and more efficient use of natural resources such as land and sunlight. For example, we can mention the use of sunlight to provide the electrical and thermal energy needed by buildings [258]. Inspired by the movement of plants such as sunflowers that follow the movement of the sun throughout the day, solar panels on buildings can be designed to follow the sun and always use direct light during the day. Also, inspired by the movement of flowers, it is possible to create mobile (rotating) buildings in which living rooms and bedrooms with large glass windows are on one side. The rooms of these buildings can be facing the sun during the summer and facing the sun during the winter. In fact, the rotation of the building increases energy intake in winter and decreases heat intake in summer. For example, we can refer to the Chameleon flower building in the city of Freiburg, Germany (**Figure 32(a)**). Other examples of bionic architecture include imitating termite mounds (**Figures 32(b)** and **32(c)**) to build buildings with a passive cooling system.) Cited. These large mounds of 3 to 8 meters, which are built by termites for living, have the ability to maintain a temperature of 29 °C. While the outside temperature varies between 1 and 40 °C during the day and night, the temperature inside the hill remains constant. This structure can be used to build buildings and shopping centers that automatically keep their temperature low during the day. Walls with different thicknesses, building a hood in the middle of the building and external-colored walls to absorb less energy can help the efficiency of the passive cooling system [259].

Figure 32 (a) Chameleon revolving building in Freiburg, Germany, (b) a picture of the termite hill and (c) the internal structure of the termite hill along with the ways made by the termites to pass air and regulate the temperature of the hill [60].

Bionics in the computer field

Today, various algorithms such as ant and bee algorithms are used in computer software. These algorithms are used to solve many problems that normally require several thousand hours of time. One of the simplest algorithms derived from nature data is the ant algorithm, which is inspired by the movement of ants between their colony and the location of food. In nature, most ants initially search for food by accident, and when they find it, they return to their colony, leaving behind a special chemical that other ants can recognize. If other ants find this path, they are more likely to follow it and stop foraging randomly. Now, other ants by following the initial path cause the secretion of more substances and, as a result, the chemicals remaining on the path become stronger. But over time, these chemicals evaporate and disappear, and the respective path loses its tracking power. This evaporation is more likely when the ant's round-trip path is long. Therefore, in small paths, the possibility of evaporation is less and with the passage of time, the movement of more ants increases the density of the chemical substance in that path [260]. Evaporation of the chemical is very important. If this did not happen, the random path found by the 1st ant would be followed by all subsequent ants and the best path would never be found and used. The effect of evaporation in the natural world on ants is not yet clear, but in computer software it is very important to find the best answer. The result of this type of movement is that whenever an ant finds a better (shorter) path to food, other ants are more likely to follow that path, and other ants give positive feedback to that path. These events are repeated until an optimal path (shortest path) is selected. Once this path is reached, all ants choose it. The idea of the ant algorithm is that the computer, with a series of simulated ants, imitates this phenomenon and solves the problem by moving on a graph. Today, such algorithms are used to solve various problems, including problems of intra-city and extra-city transportation systems. The 1st algorithm was dedicated to solving the traveling salesman problem. The goal of this problem is to choose the shortest route between a predetermined series of cities. The main algorithm dedicated to this problem is very simple and works based on a number of ants, each of which follows the possible routes between cities following a series of specific rules. **Figure 33** shows how the shortest path is selected using the ant algorithm.

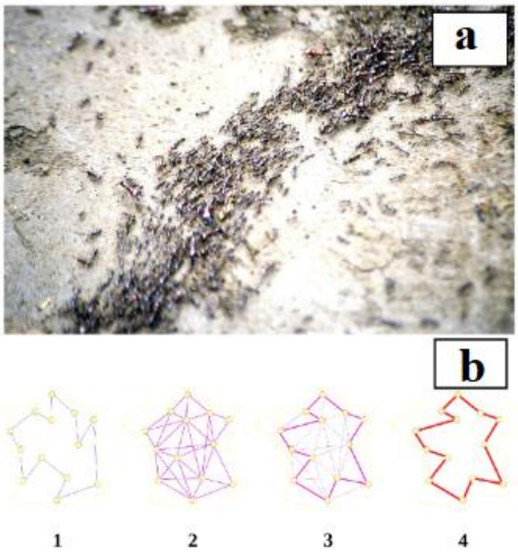


Figure 33 (a) The movement of ants between their food site and their colony, which is an inspiration for solving real problems. (b) A diagram of how to solve the traveling man problem by an ant algorithm: (1) one of the ants chooses a path and on it, it secretes its chemical substance; (2) all ants follow paths that cause chemical deposition on the paths based on the quality of the path; (3) each part of the path that is the shortest and the most ants have passed through it has more material on it; and (4) evaporation clears inappropriate paths (solution) [61].

Medical bionics and nanomedicine

Today, many equipment and devices such as artificial implants have been produced, which are either inspired by the body of living organisms or made directly from natural materials. With the significant progress that has been made in the field of combining different natural and synthesized materials, today mankind has the ability to build equipment that is able to imitate different biological organs. The important thing about this equipment is that it must be highly compatible with the human body and any other living organism to avoid any side effects such as illness or rejection by the body. Nanobioelectronic devices and equipment face 3 major challenges that must be taken into consideration [261-262].

The mechanical properties of quality electronic nanomaterials are usually different from the mechanical properties of biological materials. For example, the Young's modulus of unnatural (synthetic) electronic materials is typically between 1 and 100 GPa, while the Young's modulus of skin is between 0.1 and 1 MPa. Also, unnatural electronic nanomaterials have a breaking strain about 30 times lower than human skin. These apparent differences in mechanical properties are not only an obstacle to the compatibility of biomedical devices with the body of living organisms, but may also cause discomfort, irritation, recoil, and injury and disease [263].

The manufacturing conditions of high-quality nanoelectronics equipment are usually incompatible with the manufacturing and synthesis conditions of biological materials. While micro- and nanoelectronics devices are manufactured by "top-down" methods and under harsh environmental conditions such as high temperatures and strong acids, biological materials such as organs and skin are often produced by "bottom-up" methods.

Electronic wafers usually have planar and 2-dimensional structures, while biological materials have complex 3-dimensional structures. These incompatibilities pose major obstacles to the manufacture and use of biomedical devices, which have been resolved for a limited number of devices to date [264]. **Figure 34** shows some of these equipment's that are inspired by their natural type and are used in the human body.

Other examples in this field include medical nanorobots. In the human body and other living organisms, there are many molecular motors that are responsible for transporting and moving materials needed by cells. These motors are designed to perform mechanical movements (output) due to a suitable external stimulation (input). These types of motors are very similar to normal (large scale) motors in terms of performance. The input of molecular motors, like normal motors, can be chemical energy, light or other things that cause them to be stimulated. Among these motors, the kinesin molecular motor has the ability to move on a specific path (**Figure 35(a)**). Inspired by these motors, nanorobots can be made that are responsible for carrying medicine (**Figures 35(b)** and **35(c)**). It should be noted that natural molecular engines do not have any waste products (waste materials) and this factor increases their efficiency. On the other hand, unlike heat engines, natural molecular engines do not release heat during their operation and the reactions performed are endothermic. Also, among other bionic applications in biomedicine and nanoelectronics, we can mention nanocircuits made of graphene-based transistors and carbon nanotubes. These equipment's that can be used in the human nervous system are made to imitate the natural human nerves [265].

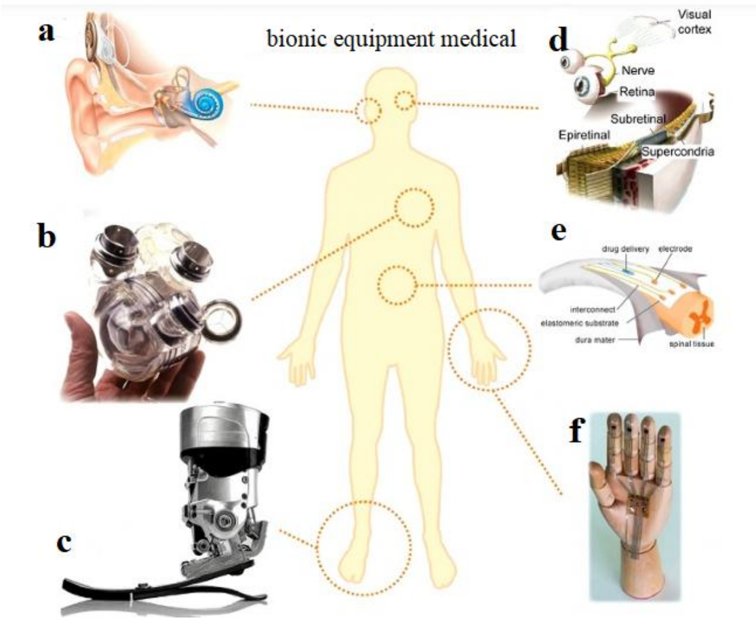


Figure 34 A number of bionic equipment in medical science that are used in the human body: (a) cochlear implant to restore hearing power (cochlear implant), (b) artificial heart, (c) artificial leg, (d) artificial eye, (e) part from the artificial spinal cord and (f) artificial skin for the hand with the ability to detect and receive mechanical stimuli such as movement and touch [62].

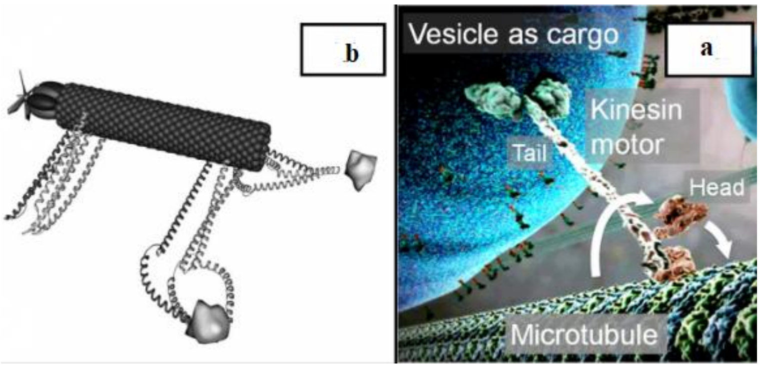


Figure 35 (a) A picture of the movement of the natural kinesin molecular motor on a specific path, and (b) a synthesized nanorobot with a carbon nanotube body for drug delivery [63].

Bionic nanomembrane sensors (infrared wave sensors)

Nanomembranes are one of the most used components in the body of living organisms, which has been used by nature since the beginning of its existence. All living cells, from bacteria to cells in the human body, use nanomembranes to connect and exchange cytoplasm mass with the surrounding environment. These membranes can be imitated to make electro-optical devices and sensors. Some biological organs are sensitive to light radiation in certain wavelength ranges of electromagnetic waves. For example, plants react to the radiation of electromagnetic waves in the range of 0.4 to 0.7 μm [266]. This feature is also present in the visual system of animals and humans. For example, the human eye receives and senses electromagnetic waves in the visible region (0.27 to 0.75 μm). This is despite the fact that the visual system (receiving electromagnetic waves) of animals may work in other wavelength ranges. This variability of sensory systems in animals is due to the fact that the organism in question can receive the best performance from its vision system, have the most sensitivity to the surrounding environment, and receive the largest amount of information from the surrounding environment. For example, the honey bee has the ability to detect electromagnetic waves in the range of yellow waves to ultraviolet waves (0.3 μm) in order to make the most of its visual system in detecting the pigment of flowers. Similarly, a number of living organisms are equipped with sensors in the infrared wavelength range. The reason for the importance of this category of sensors is that infrared waves cover more than half of the spectrum of solar rays and contain a lot of information about the living organism's environment [267-270]. On the other hand, the body of living beings such as humans emits a large part of its internal heat or energy through infrared waves. Therefore, sensors that receive and identify infrared waves have the ability to detect the body of most living organisms. For this reason, bionic sensors have attracted the attention of many researchers. Rattlesnake is one of the creatures equipped with these sensors. The sensor of this snake, which is shown in **Figure 36**, gives a very good reaction to the waves emitted from the body of warm-blooded creatures (body temperature is about 40 °C). The sensor mechanism of this snake is such that when the emitted infrared photons reach the molecular resonance frequency of the living tissue, it is absorbed by the membrane and leads to molecular vibrations, and finally, the target is identified by the sensor.

Today, rattlesnake sensors are imitated to make artificial sensors of infrared waves. These bionic sensors are generally divided into photonic and thermal. The 1st category is based on semiconductors, which have high sensitivity and must be kept at a low temperature. For this reason, this group of sensors has a high price and is difficult to use. The 2nd category (thermal sensors) work based on the excitation of photons or electrons by infrared waves in a solid body. The radiated infrared wave is absorbed by the solid body after a series of processes and causes random movement of the ions in the network and heat production. In the following, these waves can be converted into electrical pulses and transmitted in the system. The new generation of such sensors has the same sensitivity as photonic sensors and a lower price, but their response time is longer than that of photonic sensors. Synthetic nano-membranes, which are inspired by the natural nano-membrane of living organisms, especially the rattlesnake, are one of the main components of bionic sensors. Synthetic nanomembranes are plate-shaped structures with a thickness of 5 to 100 nm. The nanometer thickness of these membranes allows them to be used in the manufacture of nanoelectromechanical devices (NEMS). **Figure 37** shows an example of bionic nanomembranes. "Graphene" is one of the materials used in making these sensors. This material has a 2-dimensional (sheet) structure of carbon atoms and creates a function similar to the function of rattlesnake sensors in synthetic sensors. The extremely low thickness of graphene (about 1 nm) allows the fabrication of very thin nanometer membranes (about a few nanometers). Such membranes are used in modern infrared sensors today. **Figure 38** shows an example of infrared sensors made of graphene-based nanomembranes. The reason for the popularity of graphene for use as a bionic nanomembrane is its very high aspect ratio, very small band gap, and high conductivity [270].

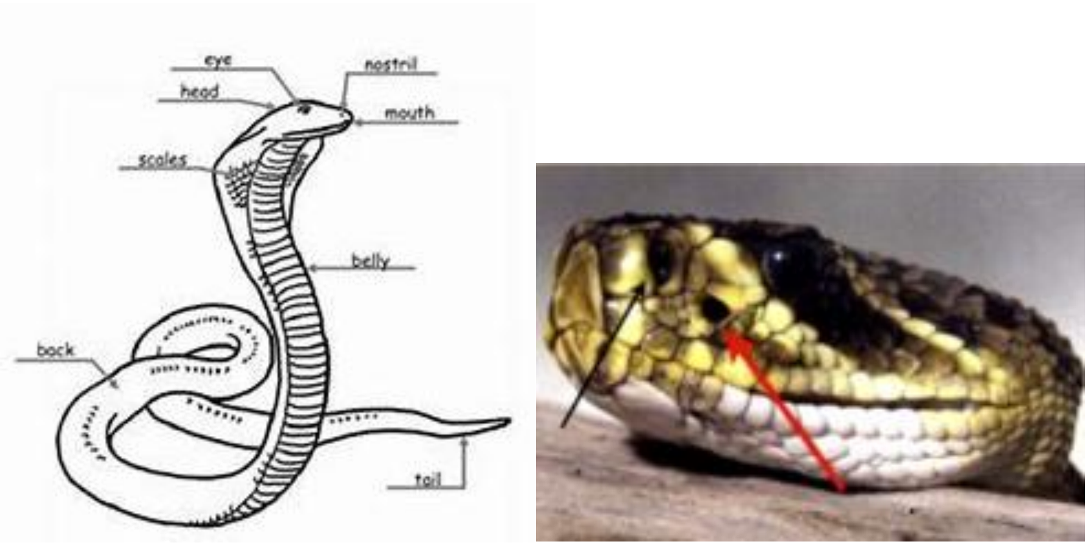


Figure 36 (a) Rattlesnake head; The red arrow shows the location of the snake's infrared sensor hole, and the black arrow shows the snake's nose. (b) A diagram of the cross-section of the snake's infrared wave sensing organ [67].

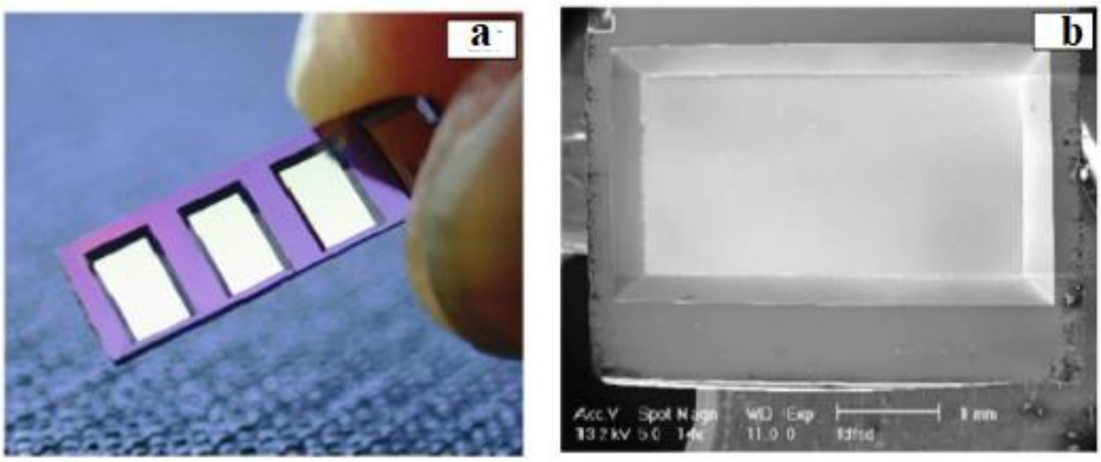


Figure 37 Nanomembrane used in infrared bionic sensors: (a) optical image of nanomembrane and (b) its electron microscope image [67].

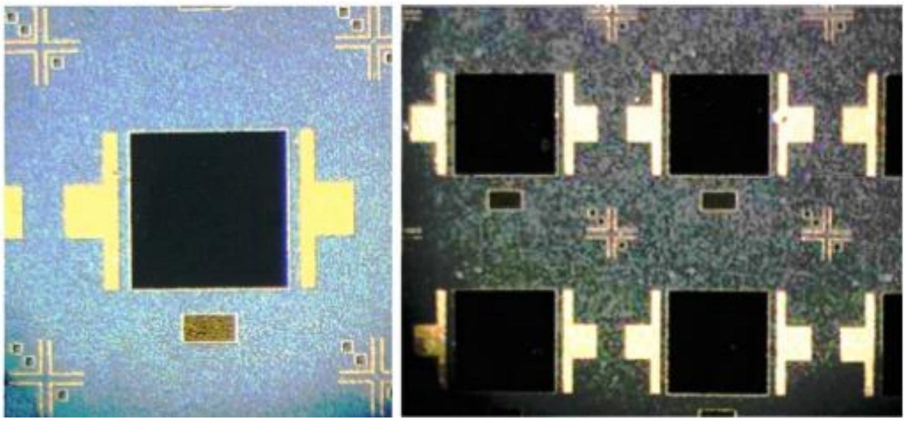


Figure 38 Image of the surface of the infrared bionic sensor made of graphene nanomembranes [67].

Bionic fuel cells

Today, electric energy is perhaps one of the most used types of energy in human societies. One of the sources of creating this energy is the energy contained in chemical fuels. The primary solution for energy production is to burn fuel to produce thermal energy and convert it into mechanical energy and then electrical energy [271-273]. This method has low efficiency and produces extra heat. This excess heat is released from the energy production cycle and warms the earth's atmosphere. On the other hand, the "electrochemical conversion method" to convert the chemical energy of the fuel into electrical energy is a highly efficient and isothermal method and does not have the limitations of the Carnot cycle. Batteries and fuel cells are 2 examples of man-made generators that work based on electrochemical conversion. Regardless of the many similarities that batteries and fuel cells have, unlike batteries, fuel cells use external chemical sources to produce electrical energy. Fuel cells have different types, the most famous of which are cells based on proton exchange membranes. Photon Exchange Membrane (PEM)). **Figure 39** shows the working method of this type of cells. The central part of these cells consists of a thin non-conductive membrane in which protons have a high permeability [274-276]. On the anode side of the cell, hydrogen gas is decomposed into electrons and protons by platinum Nano catalysts coated on the anode. The generated electron on the anode side is collected and sent to the external circuit to generate electricity. Simultaneously, the produced protons migrate from the membrane path towards the cathode. On the cathode side, protons and electrons are combined with oxygen by the platinum catalyst and produce water molecules and return them to the environment. The mathematical expression of fuel cell reactions is given in Eqs (1) and (2). Although fuel cells do not emit any heat, their practical efficiency is around 40 %. Of course, the theoretical efficiency of solar cells can be up to 90 % [277-278].

$$H_2 \rightarrow 2H + 2e^- \ (Er = {}_0V) \quad (1)$$

$$O_2 + 4H + 4e^- \rightarrow 2H_2O \ (Er = 1.23V) \quad (2)$$

The most important part of fuel cells is their proton exchange membrane. The main function of this membrane is to pass protons and at the same time prevent the passage of gases and electrons. One of the most common membranes is the Nafion membrane, which has a low efficiency and increases the complexity and price of the fuel cell. Theoretically, the linear path between 2 electrodes is the best and most efficient path for proton transfer. But Nafion has irregular holes with different shapes, which causes the proton to move in a winding and random path. In fact, the proton transfer in Nafion is done by the vehicle mechanism, which has a low efficiency. In general, protons are transported across the membrane by 2 mechanisms [276-280]:

1) The "carrier" mechanism in which the hydrogen ion (proton) is transferred with water molecules and the result is the transfer of water along the membrane.

2) "Grotthuss transport" mechanism in which the proton is transferred along a chain of water molecules. In this method, the water molecules remain fixed in place and the proton is moved along the path as a defect. Therefore, the water molecule is not moved along the membrane and the proton transfer path is closer to the direct pat

The helical molecule gramicidin A (gramicidin A) is one of the natural components that can be inspired by making fuel cells with a direct proton transfer pathway.

This molecule with its twisted structure is located in the phospholipid bilayer membranes and creates a direct path for the passage of protons through the membrane (**Figure 40(a)**). By imitating this structure and using a carbon nanotube filled with water (**Figure 40(b)**), it is possible to create a direct path for proton transfer through the Gratus mechanism in the middle membrane of fuel cells. This work significantly increases the efficiency of fuel cells.

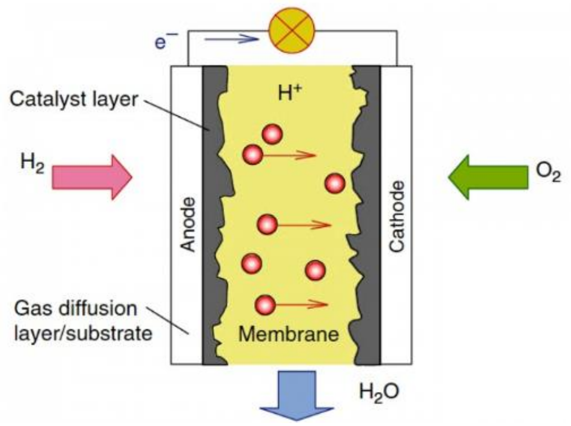


Figure 39 A diagram of how electrochemical reactions are carried out in a PEM fuel cell [2].

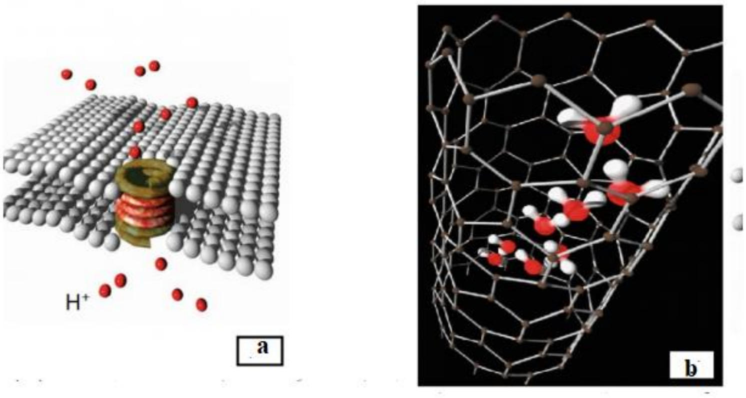


Figure 40 Helical gramicidin A molecule in the natural phospholipid membrane (a) and the blue wire inside the carbon nanotube for proton transfer with the Gratus transport mechanism (b) [59].

Synthesis of metal nanoparticles used in electronic equipment

The synthesis and customization of metal nanoparticles is one of the important research fields for the construction of nanoelectronics devices based on nanoparticles. The synthesis method of these particles can affect their size, shape, quality, and other properties, and the result is a change in their physical, chemical, and electrical properties. For this reason, the synthesis method of metal nanoparticles is extremely important in nanoelectronics applications such as sensors, catalysts, nanobioelectronic and optoelectronic equipment [281-283]. So far, a wide range of synthesis methods based on physicochemical mechanisms have been proposed for metal nanoparticles. Most of these methods are very active and cause environmental and biological problems and hazards. On the other hand, biomimetic synthesis methods that use non-toxic substances found in nature are safe and environmentally friendly methods [284-286]. For example, silver nanoparticles are one of the metal nanoparticles that are used in nanoelectronics equipment, especially in medicine. In the biomimetic methods introduced for the synthesis of silver nanoparticles, natural materials such as chamomile plant extract, lemon leaves, tamarind tree leaves, and black pepper are used [287-290].

Nanoelectronics scaffolds

Nanoelectronics scaffolds (nanoESs), which are made by imitating the biological components of the body, are 3-dimensional porous materials that consist of an interconnected network of nanowire field effect transistors and biological cells are grown on them. These scaffolds can be used as extracellular scaffolds in the growth of nerves, muscle and heart cells. **Figure 41** is the process It shows the construction of these scaffolds [67].

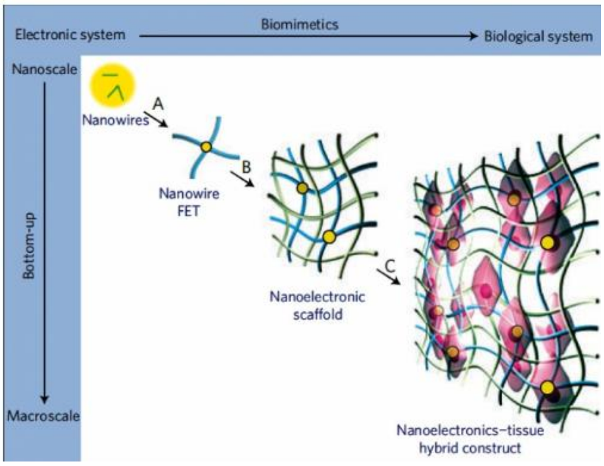


Figure 41 Schematic of the process of making nanoelectronics bionic scaffolds based on field-effect nano transistors for the growth of different body cells with the bottom-up method [67].

Molecular nanoelectronics

In this field of nanoelectronics, molecular units are used to make electronic devices. These materials can be used in several ways: 1) single molecule, 2) molecular self-assembly monolayer and 3) thin layer of molecular material. In the 1st case, electronic structures are made based on a certain molecule. In other words, the electronic properties of a molecular unit and its band structure are used to design the structure. In the 2nd and 3rd case, the properties of electron transfer in the set of molecular units are used. **Figure 42** shows a diagram of molecular nanoelectronics structures. These structures are used in energy storage, transistor manufacturing and integrated circuits [291-293].

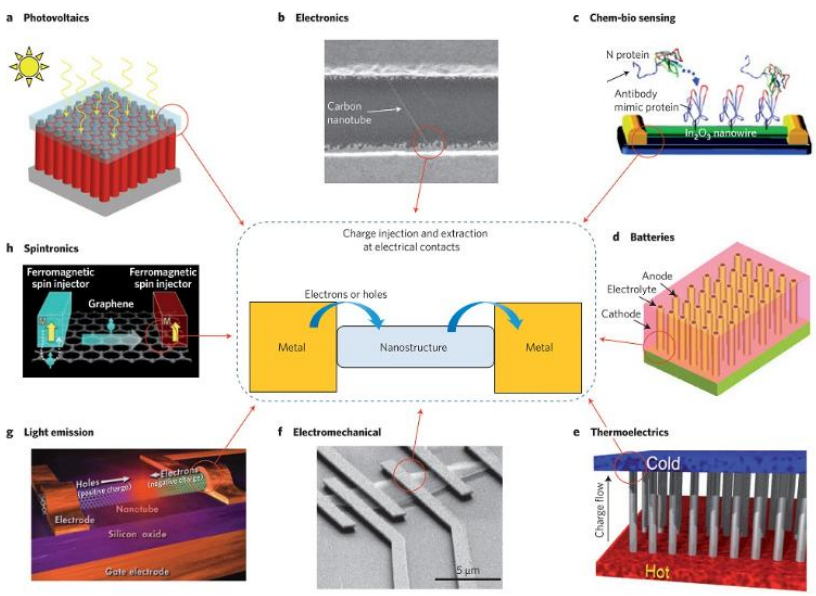


Figure 42 A list of molecular nanoelectronics devices: (a) Photovoltaic devices such as solar cells, (b) Field effect transistors based on carbon nanotubes, (c) Biological-chemical sensors, (d) Lithium-ion batteries, (e) Thermoelectric devices, (f) Graphene-based electromechanical system, (g) carbon nanotube-based light emitting electronic devices and (h) graphene-based spintronic devices [67].

Nanoscale integrated circuits

It can be said that the most important part of an electronic structure is its electronic circuit. Integrated circuits consist of a large number of electronic units such as diodes and transistors, which are connected together by connectors such as wires [294-295]. If all the components of an integrated circuit can be reduced to molecular or nanometer dimensions, we can witness the construction of new nanoscale electronic circuits and structures. This work has been pursued in the field of nanoelectronics and so far, very attractive products have been produced on an industrial scale. To put it more simply, transistors and diodes have been produced in nanometer form, and nanowires or molecular arrays have been used as wires in circuits [296]. **Figure 43** shows an integrated circuit whose dimensions have reached the limit of several nanometers with the progress of the nanoelectronics field. The main problem in these devices is the very high heat that occurs during the operation of the structure. The reason for this is the small cross section of the flow.

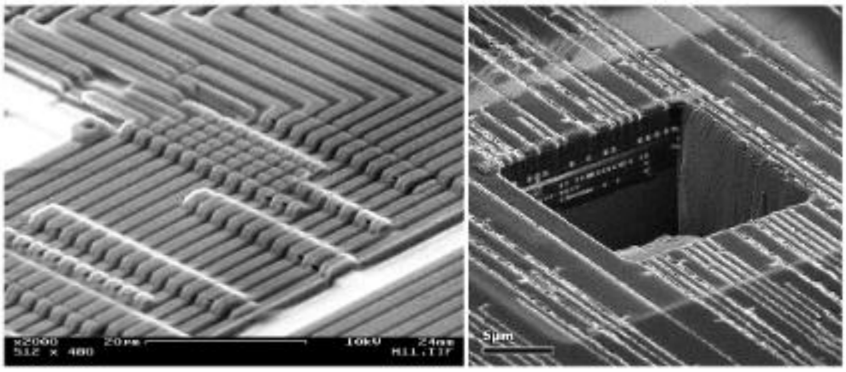


Figure 43 A part of the electronic circuit using nanowire arrays [67].

Nanostructured artificial organs

Artificial organs are a group of devices that replace a part of the body of living organisms to perform its functions in the absence of the organ. This new field can be related to nanoelectronics with 2 different approaches [297-298]:

1) The artificial organ consists of an electronic structure with nanoscale components. For example, we can refer to the artificial eye or the system of connecting artificial organs to the body of a living being.

2) The artificial organ has nanostructured components that need to be coordinated with electronic devices to perform the desired tasks.

The most important nanoelectronics artificial organs are brain Nano sensors and artificial eyes. In these devices, an attempt is made to restore part of the damaged system of the human body by using electronic circuits so that the organ can continue to function. The most important requirements of a nanoelectronics artificial organ are the high biocompatibility of the materials used, coordination with the body parts of organisms, high chemical stability in the body's environment, and the ability to repair or replace it.

Lab-on-a-chip

Lab-on-a-chip (Lab-on-a-chip) is a device in which several laboratory tasks are performed instantly and the results are displayed instantly. In fact, instead of performing several tests in a laboratory, this system receives the sample and by performing certain operations on it, performs the test and presents the output data in tangible form [299]. **Figure 44** shows the advantage of lab-on-a-chip compared to laboratory work. In general, lab-on-a-chip consists of 3 main parts: 1) drive part, 2) sensors, and 3) circuits and displays. The driving part produces mechanical, magnetic or electrical forces and tries to stimulate the test sample. After the sample is stimulated, the sensors measure the sample's electrical, optical, or magnetic properties. Circuits and displays also have the task of collecting and displaying the obtained information. Lab-on-a-chip is related to the field of nanoelectronics in 2 aspects: 1) nanoscale circuits and 2) nanoscale sensors. Recent lab-on-a-chip studies have tended toward the development of high-performance circuits and nanometer sensors [300].

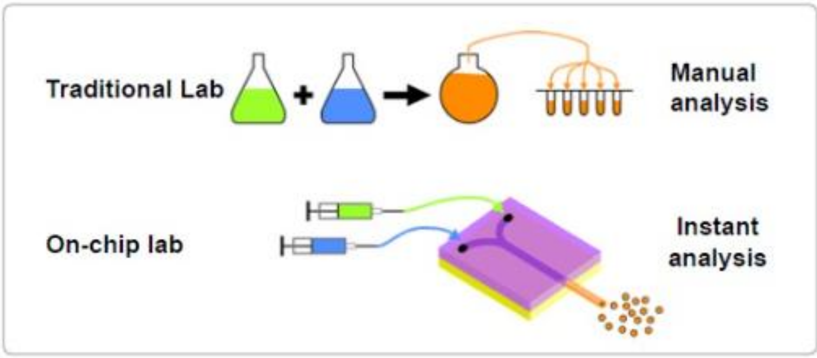


Figure 44 Comparison of common laboratory operations and lab-on-a-chip performance [67].

Conclusion, challenges and future prospects

Due to the special chemistry of carbon atoms, carbon structures have a wide range of properties in various fields of nanoelectronics and bioelectronic technology. Among allotropes of carbon, carbon nanotube is of particular importance due to its elongated structure and tunable conductivity behavior. In this article, the electrical conductivity of this group of materials was investigated. It was said that these materials can have a wide range of electronic and electrical behaviors depending on their chirality, apparent diameter, number of walls and working temperature. It was emphasized that by controlling each of these parameters as well as doping these materials with suitable elements, their semiconducting behavior can be strengthened. This factor has made it possible to use carbon nanotubes in the construction of devices that require semiconductors with a variable bandgap. The most important of these materials are field effect Nano transistors and nanodiodes with p-n junctions. In Nano transistors, carbon nanotubes are used as conduction channels and in nanodiodes as integrated p-n junctions. The advantage of using this material in the manufacture of the aforementioned devices is their miniaturization and the possibility of changing the electronic behavior using process variables.

Graphene is a semiconductor material with 0 bandgap and its conduction and capacitance bands intersect at Dirac points. This material has a very high electrical conductivity. In this article, the electrical properties and applications of graphene were investigated. It was said that graphene does not have a bandgap, and this causes the main limitation in graphene-based transistors, i.e. “low on/off ratio”. It was emphasized that structural defects significantly affect the electron transport properties of graphene nanostructures. The 3 main types of defects affecting these properties are: Vacancies, impurities and topological defects. Nanoscale transistors and DNA sequencing, as 2 important applications of graphene, were discussed in detail. The advantage of using graphene in nanoscale transistors is their 2-way penetration. It was also said that unlike transistors made of conventional semiconductors with significant bandgaps, graphene-based field-effect transistors do not turn off completely. In this article, field effect transistors and DNA sequencing were introduced as 2 main applications of graphene nanostructures. The use of graphene in DNA sequencing was explained in such a way that the displacement of the DNA molecule causes the ions to be pushed out of the volume of the graphene cavities and, as a result, causes a temporary decrease in the ion current. The amount and duration of electrical current blockage provide us with information about the diameter and length of the DNA molecule, respectively.

The current article sought to provide a suitable definition of organic materials to enter the discussion of organic nanoelectronics. To achieve this definition, the history of the development of organic materials and the sources from which these materials were produced were studied. It was said that the main backbone of organic substances are H-C bonds, and metal ions may also be used in their molecular structure. It was emphasized that the chemical formula of a particular compound may be similar to organic substances, but in order for this substance to be accepted as an organic substance, the backbone of its molecules must consist of hydrogen-carbon bonds. The strengths and weaknesses of organic materials for nanoelectronics applications were reviewed and the most important advantages of organic materials for use in electronic applications were discussed. Finally, several examples of the most important applications of organic materials in nanoelectronics devices were introduced and the role of these materials in the construction of organic light emitting diodes (OLEDs) and organic thin film transistors were studied. It was emphasized that today, organic nanoelectronics materials can compete with silicon-based electronic devices, and their efficiency can be further increased by improving synthesis methods and manipulating the molecular structures of these materials.

In this article, organic substances are referred to substances whose backbone of molecular structure consists of carbon-hydrogen bonds. It was said that more than 16,000 types of organic materials with different molecular and chemical structures have been produced so far, but only a limited number of these materials have been able to be used in organic-based nanoelectronic devices. These materials include: organic charge transfer complexes, conductive or conjugated polymers with π bonds, conductive gels, and dielectric polymers. An attempt was made to introduce the general principles of each of the mentioned cases and to express their importance in the field of nanoelectronics in simple language. It was said that organic charge transfer complexes are 3-dimensional arrays of electron donor and acceptor centers, and the electric charge is transferred between these areas. In contrast, conductive polymers have molecules with alternating single and double bonds, where the electric charge is moved along the chain by resonance of the bonds forming the backbone of the molecular units. Also, conductive gels are the same as conductive polymers, with the difference that the molecules that make up these materials have self-assembly properties and their constituent units can absorb part of the incident light wavelength and exhibit photoluminescence properties. Unlike the 3 mentioned cases, whose main application is high conductivity, insulating polymers also have special applications in the manufacture of nanoelectronics devices. These materials resist the passage of electron current and play the role of insulation in electrical applications. The purpose of this article is to prepare readers to enter the advanced applications of organic materials in nanoelectronics.

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