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Review

Nanosensors in environmental analysis

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Abstract

Nanoscience and nanotechnology deal with the study and application of structures of matter of at least one dimension of the order of less than 100 nm (1 nm = one millionth of a millimetre). However, properties related to low dimensions are more important than size. Nanotechnology is based on the fact that some very small structures usually have new properties and behaviour that are not displayed by the bulk matter with the same composition.

This overview introduces and discusses the main concepts behind the development of nanosensors and the most relevant applications in the field of environmental analysis. We focus on the effects (many of which are related to the quantum nature) that distinguish nanosensors and give them their particular behaviour. We will review the main types of nanosensors developed to date and highlight the relationship between the property monitored and the type of nanomaterial used.

We discuss several nanostructures that are currently used in the development of nanosensors: nanoparticles, nanotubes, nanorods, embedded nanostructures, porous silicon, and self-assembled materials. In each section, we first describe the type of nanomaterial used and explain the properties related to the nanostructure. We then briefly describe the experimental set up and discuss the main advantages and quality parameters of nanosensing devices. Finally, we describe the applications, many of which are in the environmental field.
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Keywords: Sensors; Environment; Carbon nanotubes; Nanotechnology

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Contents

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1. Introduction

Nanoscience and nanotechnology deal with the study and application of structures of matter with at least one dimension of the order of less than 100 nm (1 nm = 10^{-9} m). This is the standard way of classifying what belongs to the 'nano' world.

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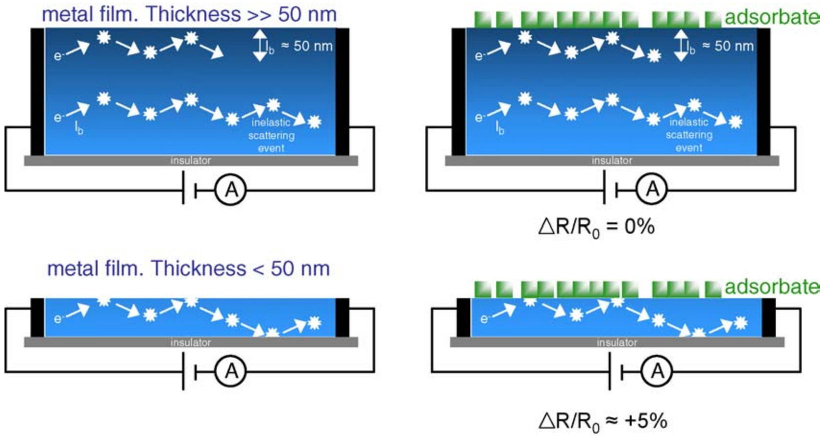

Fig. 1. Change in the measured property as a function of the thickness in resistive gas sensors. When the thickness is high (upper figure), the electrical resistance does not change because the inelastic scattering events in the bulk predominate. When the thickness of the metal film is low (lower figure), the adsorbed target molecules can be detected by measuring the change in the electrical resistance.

However, properties related to low dimensions are more important than size. Nanotechnology is based on the fact that some structures usually smaller than 100 nm have new properties and behaviour that are not exhibited by the bulk matter of the same composition.

This is because particles that are smaller than the characteristic lengths associated with the specific phenomena often display new chemistry and new physics that lead to new properties that depend on size. Perhaps one of the most intuitive effects is due to the change in the surface/volume ratio. When the size of the structure is decreased, this ratio increases considerably and the surface phenomena predominate over the chemistry and physics in the bulk. Fig. 1 shows an example of this effect (change in the measured property when the surface/volume ratio of the particle decreases) in resistive gas sensors (thin metal films).

Therefore, although the reduction in the size of the sensing part and/or the transducer in a sensor is important in order to better miniaturise the devices, nanoscience deals with new phenomena, and new sensor devices are being built that take advantage of these phenomena. New effects appear and play an important role that is often related to quantum mechanics and quantum mechanisms. Consequently, important characteristics and quality parameters of the nanosensors can be improved over the case of classically modelled systems merely reduced in size. For example, sensitivity can increase due to better conduction properties, the limits of detection can be lower, very small quantities of samples can be analysed, direct detection is possible without using labels, and some reagents can be eliminated.

Sensors have been classified according to multiple criteria [1]. The most common way to group sensors considers either the transducing mechanism (electrical, optical, mass, thermal, piezoelectric, etc.), the recognition principle (enzymatic, DNA, molecular recognition, etc.) or the applications (environmental, food, medical diagnosis, etc.). In this overview, we focus on the properties that characterise nanosensors and give them their particular behaviour. With particular focus on applications in the environmental field, we discuss the main types of nanosensors developed to date and highlight the relationship between the property monitored and the type of nanomaterial used.

In this article, we discuss several nanostructures that are currently used in the development of nanosensors, nanoelectrodes and nanodevices. In particular we focus on the main nanostructures, i.e. nanoparticles, nanotubes and nanorods. In each section we first describe the type of nanomaterial used and explain the properties related to the nanostructure. We then briefly describe the experimental set up and discuss the main advantages and quality parameters of nanosensing devices. We do not intend to provide a complete overview of the available literature, but we introduce and describe the current state of the art of nanosensors and their applications in the environmental field.

2. Sensors based on nanoparticles and nanoclusters

Nanoparticles (NPs) are clusters of a few hundred to a few thousand atoms that are only a few nanometres long. Because of their size, which is of the same order as the de Broglie wavelength associated with the valence electrons (following the wave-corpuscle duality principle, each particle can be described as a wave with wavelength λ), nanoparticles behave electronically as zero-dimensional quantum dots with discrete energy levels that can be tuned in a controlled way by synthesizing nanoparticles of different diameters. A quantum dot is a location that can contain a single electrical charge, i.e. a single electron. The presence or absence of an electron changes the properties of a quantum dot in some useful way and they can therefore be used for several purposes such as to information storage or useful transducers in sensors. Nanoparticles have outstanding size-dependent optical properties that have been used to build optical nanosensors primarily based on noble metal nanoparticles or semiconductor quantum dots.

In noble metals, nanostructures of smaller size than the de Broglie wavelength for electrons lead to an intense absorption in the visible/near-UV region that is absent in the spectrum of the bulk material. The conduction electrons are then trapped in these “metal boxes” and show a characteristic collective oscillation that leads to the surface plasmon band (SPB) observed near 530 nm for nanoparticles in the 5–20 nm range. This extinction band arises when the incident photon frequency is resonant with the collective oscillation of the conduction electrons and is known as the localized surface Plasmon resonance (LSPR) [2,3]. This LSPR is responsible for the brilliant colours of the nanoparticles that have been used since ancient times to provide the bright colours of stained glass in cathedrals.

The LSPR spectrum depends on the NP itself (i.e. its size, material and shape) but also on the external properties of the NP environment [4]. This makes noble metal NPs extremely valuable from the sensing point of view [5]. LSPR spectra are extremely sensitive to changes in the local refractive index. The local refractive index changes when molecules are attached to the metal NPs. This produces a shift in the LSPR spectrum that can be used to detect molecules attached to the noble metal NPs. The selectivity of the sensor is achieved by chemically modifying the NPs with self-assembled monolayers (SAMs) that can be tailored to incorporate a wide variety of molecular recognition elements such as enzymes, antibodies or DNA [6]. Fig. 2 shows the sensing principle of LSPR sensors.

From the instrumental point of view, LSPR nanosensors can be implemented using small, light, robust, extremely simple and inexpensive equipment for unpolarized UV–vis extinction spectroscopy in transmission mode. The glass containing the arrays of NPs is inside a flow cell that is coupled to a source of white light and a miniature spectrometer through an optical fibre. The cell is also linked directly to a solvent reservoir and to a syringe containing the analyte to be detected [6].

LSPR-based sensors have been used in biosensing. For instance, streptavidin was quantitatively detected with a sub-picomolar limit of detection using triangular silver NPs with biotinylated self-assembled monolayers (SAMs) [7]. The arrays of triangular silver NPs were fabricated using Nanosphere Lithography [8]. Biotynilated SAMs have also been used in immunoassays to detect the antibody, anti-biotin [9]. The limit of detection was estimated at <700 pM.

LSPR sensors based on a single NP have recently been developed. From the instrumental point of view, UV–vis spectroscopy cannot be used to measure the LSPR spectrum of individual NPs because even in the most favourable experimental conditions the absorbance of a single NP is very close to the detection limit. Instead, resonant Rayleigh scattering spectroscopy is the most straightforward way to characterize the LSPR spectra of individual noble metal NPS. The advantage of scattering spectroscopy lies in the fact that the scattering signal is detected in the presence of a very low background [10]. The light scattered by the NPs can be measured with a dark-field microscope.

For example, McFarland et al. used individual silver nanoparticles to detect hexadecanthiol molecules with zeptomole sensitivity [10]. Raschke et al. [11] also built a single-nanoparticle optical sensor that detects the protein streptavidin using 40 nm gold NPs functionalized with biotin. This biosensor can detect as few as 50 molecules of bound streptavidin. This opens the door to multi-analyte sensing platforms in which every NP selectively detects one analyte [10]. LSPR biosensors could be used for environmental purposes to detect viruses, bacteria or other microorganisms in water. In this case, the NPs should be functionalized with antibodies that are sensitive to the microbial toxins [1].

LSPR biosensors are an exciting alternative to today's immunosensors. LSPR biosensors have zeptomole (10^{-21}) sensitivity. This high sensitivity can approach the single-molecule limit of detection for large biomolecules. Also, only very small sample volumes (i.e. attolitres, 10^{-18}) are needed to achieve a measurable response. LSPR sensors could, in theory, be reduced to chips as small as 100 nm using single NP spectroscopy techniques. LSPR biosensors also satisfy other major prerequisites for biological studies: they are robust and durable, they are effective under physiological conditions and they react minimally to non-specific binding [7].

The size-dependent properties of noble metal NPs have also been used for ion sensing. Liu et al. [12] built a colorimetric nanosensor based on gold NPs functionalised with a Pb^{2+}-dependent enzyme. The sensing principle is based on the change in colour from red to blue when gold NPs approach each other and aggregate. In the absence of Pb^{2+}, the NPs assembled

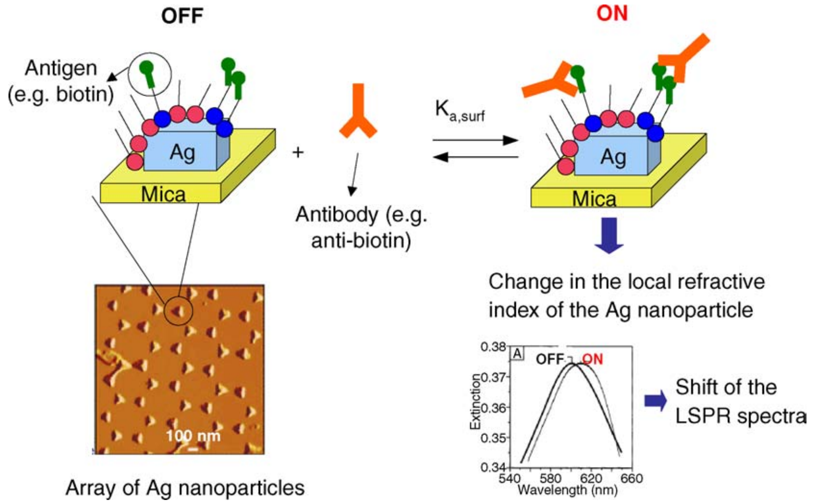

Fig. 2. Biosensing mechanism of silver pyramidal nanoparticle arrays using Localised Surface Plasmon Resonance to measure local changes in the refractive index of the Ag nanoparticles. (Reprinted with permission of [9]).

gradually. If the Pb^{2+} was present, the substrate was cleaved by the enzyme, thus inhibiting NP aggregation. Elghanian et al. [13] had used the same principle for the colorimetric detection of polynucleotides.

The LSPR excitation of noble metal NPs also enhances local electromagnetic fields responsible for the intense signals observed in all surface-enhanced spectroscopies. For example, NPs made from silver and gold are known to enhance Raman light scattering by factors of up to 10^{14} [14,15]. Cao et al. [16] used surface enhancement Raman scattering (SERS) to tag DNA and RNA targets. This biosensor was based on 13 nm gold nanoparticles functionalised with both Raman-active dyes and oligonucleotides. The oligonucleotides attached to the NPs can be used to tag unlabelled complementary DNA and RNA targets. These tags can then be detected from the Raman scattering of the dye molecules. The authors were able to simultaneously distinguish six dissimilar DNA targets and two RNA targets. They reported that, because Raman spectral signals from the different dyes were so different, it was easy to image each dye bound to the same array separately. The detection limit of this sensor was 20 femtomolar. From the environmental point of view, this type of biosensor could be used to identify pathogens in water by functionalising the NPs with oligonucleotides that are complementary to the DNA sequences of the pathogens [1].

Semiconductor quantum dots (QDs, which are nanocrystals of inorganic semiconductors with diameters of 2–8 nm) have been used to develop optical sensors based on fluorescence measurements [17]. The band gap of these semiconductor nanocrystals depends on the size of the nanocrystal. So, the smaller the nanocrystal, the larger the difference between the energy levels and, therefore, the wider the energy gap and the shorter the wavelength of the fluorescence. For example, small CdSe nanocrystals (i.e. 2.5 nm in diameter) have green fluorescence whereas large ones (i.e. 7 nm in diameter) have red fluorescence [18]. Therefore, by adjusting the size during the synthesis of semiconductor nanocrystals, basically all fluorescence colours in the visible region can be obtained [19]. Quantum dots overcome two disadvantages of fluorescence dyes: they have size-tunable fluorescence emission and are highly resistant to photobleaching, thus making them useful for continuously monitoring fluorescence and for sensing [17].

The main application of QDs as sensors exploits the Forster resonance energy transfer effect (FRET) [17,20,21]. FRET changes the fluorescence from QDs from an ON state to an OFF state. FRET occurs when the electronic excitation energy of a donor fluorophore is transferred to a nearby acceptor molecule without exchanging light between the donor and the acceptor [20]. QDs are promising donors for FRET applications thanks to the continuously tunable emissions that can be matched to any desired acceptor and to their broadband absorption, which allows excitation at short wavelengths without exciting the acceptor. The acceptor can be any molecule that absorbs radiation at the wavelength of the donor emission, e.g. another NP or an organic dye.

Transfer efficiency increases as the spectral overlap between the donor emission and the acceptor absorption increases. It also increases as the donor and acceptor molecules are brought closer together. In this sense, the quenching with QDs is not as effective as with dyes. This is because QDs are much bigger than dyes, so the donor and acceptor molecules cannot be as close. Therefore, the sensitivity of QD biosensors is limited because higher acceptor concentrations are needed to produce a large signal (i.e. an acceptable fluorescence quenching) [20].

Goldman et al. [22] used QDs functionalized with antibodies to perform multiplexed fluoroimmunoassays for simultaneously detecting four toxins. This type of sensor could be used for environmental purposes for simultaneously identifying pathogens (like cholera toxin or ricin) in water. The FRET principle was also used to build a maltose biosensor [20,21]. The sensing mechanism involved using semiconductor QDs conjugated to a maltose binding protein covalently bound to a FRET acceptor dye. In the absence of maltose, the dye occupies the protein binding sites. Energy transfer from the QDs to the dyes quenches the QD fluorescence. When maltose is present, it replaces the dye and the fluorescence is recovered.

Other optical sensors have been developed with sub-micron probes that contain dyes whose fluorescence is quenched in the presence of the analyte to be determined. These types of nanosensors are known as PEBBLEs (i.e. Probes Encapsulated By Biologically Localized Embedding) and are used mainly in intracellular sensing [23]. In this kind of nanosensor, the fluorescent dye is encapsulated within an inert matrix that protects the dyes from interferences in the sample such as protein binding. The main classes of PEBBLE nanosensors are based on matrices of cross-linked polyacrylamide, cross-linked poly(decylmethacrylate) and sol-gel silica. These matrices have been used to fabricate sensors for H^+, Ca^{2+}, K^+, Na^+, Mg^{2+}, Zn^{2+}, Cu^{2+} and Cl^-. Most PEBBLE sensors have so far been based on the measurement of single fluorescence peak intensity. In most practical applications, however, these sensors have been problematic because of signal fluctuations that were not directly caused by the concentration of the analyte. These fluctuations can be due to light scattering or to fluctuations in the excitation source (i.e. the higher the excitation power, the greater the intensity of the fluorescence). Ratiometric PEBBLE sensors overcome this problem. In this kind of sensor, a fluorescent indicator dye and a fluorescent reference dye are encapsulated inside the inert matrix. The sensor response is based on intensity ratios between the indicator and reference dyes. Ratiometric PEBBLE sensors provide more accurate results because fluorescence fluctuations not directly caused by the analyte concentration affect the indicator and reference dyes in the same way [23]. Recently, Lee et al. [24] built a ratiometric PEBBLE oxygen sensor. This sensor is based on ormosil nanoparticles containing a reference dye and an indicator dye whose fluorescence is quenched in the presence of oxygen. The sensor has very good sensitivity, a linear response over the whole range (from 0 to 100% oxygen-saturated water) and no interference from CO or NO. It could be used to monitor the oxygen dissolved in water as a measurement of the bacteria contained in water [1]. Wang et al. [25] developed a fluorescence sensor to selectively detect Cr(VI). When the sensor was applied to wastewater the results were satisfactory: no interferences affected the measurement and concentrations around 10^{-5} mol L^{-1} were quantified with recovery values ranging between 98.3 and 102.8%. The sensor is based on the selective fluorescence quenching of 1-pyrenemethylamine organic NPs in the presence of Cr^{6+}. In this way, Cr^{6+} can be determined without the separation of Cr^{3+}.

Chemical sensing of gases is crucial for a number of environmental applications. Using nanoparticle films increases the sensitivity of gas sensors because the surface area of the sensor increases [26]. For example, Baraton et al. [27] used SnO_2 nanoparticles to monitor air quality. The gases were detected through variations of the electrical conductivity when reducing or oxidizing gases were adsorbed on the semiconductor surface. The gas detection thresholds of these sensors were 3 ppm for CO, 15 ppb for NO_2 and O_3, and 50 ppb for NO. Hoel et al. [26] used WO_3^- based gas sensors to detect H_2S, N_2O and CO. 5 ppm of H_2S increased the conductance of the sensor by about 250 times, even at room temperature.

Nazzal et al. [28] observed that the photoluminescence of CdSe nanocrystals incorporated into polymer thin films changed reversibly and rapidly to gases such as benzylamine and triethylamine. The responses were so sensitive that several tens of nanocrystals were enough for detection. However, the disadvantage of the sensor was that, due to the oxidation of one layer of the nanocrystals, the CdSe nanocrystals responded irreversibly to oxygen. Nevertheless, this phenomenon could open the door to new gas sensors based on high-quality semiconductor nanocrystals [28].

Magnetic NPs have also been used in sensor applications. They can be prepared in the form of superparamagnetic magnetite (Fe_3O_4), greigite (Fe_3S_4), Maghemite (γ-Fe_2O_3), and various types of ferrites ($MeO \cdot Fe_2O_3$, where Me=Ni, Co, Mg, Zn, Mn, etc.), etc. [29]. Bound to biorecognitive molecules (i.e. DNA, enzymes, etc.), magnetic NPs can be used to enrich the analyte to be detected. Therefore, the sensitivity of the sensors can be substantially improved by using magnetic nanoparticles [30]. Magnetic NPs are also used in immunoassays because, since the magnetometer is only sensitive to ferromagnetic substances that are rarely present in the sample, the interference of the sample matrix is very low [29]. For instance, enzyme-linked immunosorbent assay (ELISA) has been used with magnetic NPs as carriers. The antimouse IgG antibody was immobilized on magnetic NPs. A good relationship between the luminescence and the mouse IgG concentration was obtained in the 1–10^5 fg/cm^3 range. Moreover, using magnetic NPs also substantially shortened the assay time [31].

Chemla et al. [32] developed a new technique for detecting biological targets using antibodies labelled with magnetic NPs. This technique uses a highly sensitive superconducting quantum interference device (SQUID) that only detected the antigen-antibody magnetic NPs. The NPs unlabelled to the antigen were not detected due to their rapid relaxation after pulses of magnetic fields were applied. In this way, the ability to distinguish between bound and unbound labels enables homogeneous assays to be run without the need to separate the unbounded particles. As in the case of other biosensors, magnetic NP sensors could be used for environmental purposes to detect toxins using magnetic NPs functionalized with antibodies.

3. Sensors based on nanowires and nanotubes

Carbon nanotubes (CNTs) are some of the most striking nanometric structures. These chemical compounds, whose structure is related to that of fullerenes, consist of concentric cylinders a few nanometres in diameter and up to hundreds of micrometres in length. These cylinders have interlinked hexagonal carbon rings. They were discovered in 1991 by the Japanese scientist Sumio Iijima [33] in the soot resulting from an electrical discharge when using graphite electrodes in an argon atmosphere. One of commonest ways of producing carbon nanotubes is by means of hydrocarbon pyrolysis in the presence of a metallic catalyst (e.g. molybdenum, nickel or cobalt dust). This is known as chemical vapour deposition, or CVD. They can also be produced via the vaporisation of graphite in a furnace by laser in an argon atmosphere. These nanotubes may form bundles of strings of around 0.1 mm in length or grow individually at catalytically selected points [34]. CNTs can be classified into single-walled carbon nanotubes (SWNT, for just one concentric cylinder) and multiple-walled carbon nanotubes (MWNT, for several concentric cylinders).

Carbon nanotubes are hundreds of times stronger than steel. This is partly due to their hexagonal geometry, which can distribute forces and stresses over a wide area, and partly due to the strength of the carbon–carbon links. They have unusual electronic properties derived from the ‘free’ electrons left at the surface of the tubes after the sp^2 hybridization of the carbon orbitals. Simple electronic devices including diodes, switches and transistors have recently been made using nanotubes. These devices are much smaller than their silicon equivalents that are currently used in computer chips. Several fields now take advantage of the exceptional properties of carbon nanotubes. From the nanosensing point of view, the most interesting of these properties are:

a) carbon nanotubes have a high length-to-radius ratio, which allows for greater control over the unidirectional properties of the materials produced,
b) they can behave as metallic, semiconducting or insulating material depending on their diameter, their chirality, and any functionalisation or doping.
c) they have a high degree of mechanical strength. In fact they have a greater mechanical strength and flexibility than carbon fibres.
d) their properties can be altered by encapsulating metals inside them to make electrical or magnetic nanocables or even gases, thus making them suitable for storing hydrogen or separating gases.

Covalently functionalized CNTs were soon proposed for use as probe tips (e.g. in Atomic Force Microscopy, AFM) for a wide range of applications in chemistry and biology [35]. However, it was the group of M. Dekker who paved the way for the development of CNT-based electrochemical nanosensors by demonstrating the possibilities of SWNTs as quantum wires [36] and their effectiveness in the development of field-effect transistors [37]. Once the difficulties in achieving electrical contact between CNTs and electrodes were overcome, many researchers attached various types of molecules to the CNTs and measured the effects.

Most sensors based on CNTs are field effect transistors (FET). Many studies have shown that although carbon nanotubes are robust and inert structures, their electrical properties are extremely sensitive to the effects of charge transfer and chemical doping by various molecules. The electronic structures of target molecules near the semiconducting nanotubes cause measurable changes to the nanotubes' electrical conductivity. Nanosensors based on changes in electrical conductance are highly sensitive, but they are also limited by factors such as their inability to identify analytes with low adsorption energies, poor diffusion kinetics and poor charge transfer with CNTs [38]. CNT-FETs are based on the fact that a large percentage of synthesised CNTs (around 70%) using the CVD method exhibit a semiconducting behaviour [39]. Fig. 3 shows a schematic structure of a CNT-FET.

The CNTs-FETs have been widely used to detect gases. Kong et al. [40] were probably the first to show that CNTs can be used in chemical sensors since exposing SWNTs to electron withdrawing (e.g. NO_2) or donating (e.g. NH_3) gaseous molecules dramatically increases or decreases the electrical resistance of the SWNTs in the transistor scheme. These authors also noted that CNT sensors exhibit a fast response and a higher sensitivity than, for example, solid-state sensors at room temperature. The reversibility of the CNT sensor was also easily achieved by a slow recovery under ambient conditions or by heating to high temperatures. At roughly the same time, Collins et al. [41] noted that the electrical conductance of SWNTs was modified in the presence of O_2, which makes them suitable for chemical sensing devices, Sumanasekera et al. [42] described the effect of absorbing several gas compounds in SWNT, and Zahab et al. [43] noted how water vapour affects the electrical resistance of a SWNT, reporting that minimum quantities of H_2O in the atmosphere surrounding a SWNT may change the conductivity of the SWNT from a *p*-type to an *n*-type. Shortly afterwards, Fujiwara et al. [44] studied the N_2 and O_2 adsorption properties of SWNT bundles and their structures. All these studies opened the door to the development of chemical sensors based on CNTs.

Greenhouse gases are especially important for monitoring the environment and are an important target for nanosensors made of CNT. Other gases, such as contaminating gases like NO_2 or NH_3, or interesting analytes like aqueous vapour, have also been widely studied as potential target analytes for nanosensors. Several authors have used CNT sensing devices to detect a wide range of gases without functionalizing CNTs, which means that, since CNTs are sensitive to many surrounding compounds, there must be no interference if the gas of interest is to be reliably detected.

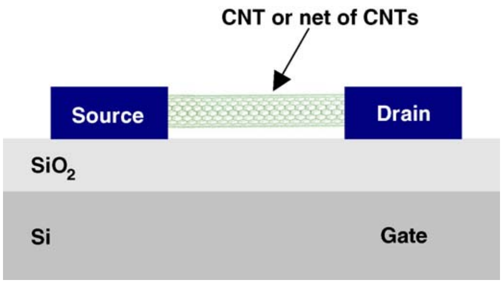

Fig. 3. Schematic structure of a Carbon Nanotube-FET. The Si substrate acts as a back gate. For measurements in solution, the substrate can be made of SiO_2 and the sample solution acts as the gate electrode.

To detect NH_3, CO and CO_2, Varghese et al. [45] investigated two different CNT-FETs electrochemical sensor geometries. The first one was a capacitive geometry with an MWNT-SiO_2 composite placed over a planar interdigital capacitor. The second was a resistive geometry with MWNTs grown over a serpentine SiO_2 pattern. Their results were mainly qualitative, detecting the presence or absence of gases over a given threshold. Ong et al. [46] also used MWNTs as a sensing device in an MWNT-SiO_2 composite layer deposited on a planar inductor-capacitor resonant circuit. The permittivity and conductivity of the MWNT-SiO_2 layer changes when different gases are absorbed, which alters the resonant frequency of the sensor. With this device, humidity, CO_2, O_2 and NH_3 can be qualitatively determined. Their results show that the sensor responses to CO_2 and O_2 are linear and reversible, but for NH_3 the responses are irreversible. Qi et al. [47] used a large array of SWNTs bridging two molybdenum electrodes to detect gases. By coating the SWNTs with polyethylene imine (PEI), they were able to detect NO_2 at less than 1 ppb but were not able to detect NH_3, CO, CO_2, CH_4, H_2 or O_2. By coating SWNTs with Nafion (a polymeric perfluorinated sulfonic acid ionomer), they selectively detected NH_3 in the presence of NO_2. Interestingly, they noted that, due to the high percentage of semiconducting SWNTs grown by CVD, the array of SWNTs exhibited semiconducting behaviour. Coating the SWNT may even change the proprieties of the FET (from a *p*-type FET without coating to an *n*-type FET when coating with PEI). It was also quite simple to recover the sensor by desorbing NO_2 with ultraviolet light illumination. The device was ultrasensitive to NO_2 (responding to 100 ppt), and the conductance vs concentration relationship was linear for NO_2 between 100 ppt and 3 ppb. Other authors developed sensors based on composite thin films of poly(methilmethaclrylate) (PMMA) with MWNTs and surface-modified MWNTs for detecting organic vapours (dichloromethane, chloroform, acetone, methanol, ethanol acetate, toluene and hexane) [48] or for detecting methane ranging from 6 to 100 ppm [49], ozone [50], and inorganic vapours such as HCl [51]. Similar devices using CNTs have been proposed for detecting H_2 [52,53], NO_2 and N_2 [54], NH_3 [53,55]. CNTs have also been proposed as effective sorbents for dioxine removal [56], which makes them potential candidates for dioxine sensors.

All the above sensing devices used CNTs without functionalization. The functionalization of CNTs is important for making them selective to the target analyte. The covalent modification of CNT sidewalls could totally change their electronic properties, making them insulators rather than semiconductors [57], so a noncovalent functionalization of CNTs is usually preferred. Kong et al. [58] coated SWNTs with a thin Pd layer (through the electron-beam evaporation of Pd nanoparticles over the entire substrate containing the SWNT device). In this way the sensing device can detect H_2, whereas raw SWNTs cannot. Shim et al. [59] coated SWNTs with PEI and observed that the SWNTs-FET changed from a *p*-type FET (without PEI) to an *n*-type FET (with PEI). They used this to qualitatively detect O_2. Fu et al. [57] coated SWNTs with a thin layer of SiO_2 that can be further functionalized with a variety of functional groups.

The above CNT sensing devices were based on changing the electrical conductivity of CNTs upon exposure to gas. Other types of sensing devices based on other principles have also been used for detecting gases with CNTs. Bundles of SWNTs [60] (about 1 mm × 2 mm × 0.1 mm) have measured the thermoelectric qualitative response to a variety of gases (He, N_2, H_2, O_2 and NH_3). Sumanasekera et al. [61] created a thermoelectric chemical sensor to measure the easily detectable and reversible thermoelectric power changes of SWNTs when they are in contact with He, N_2 and H_2. Chopra et al. [62] developed a circular disk resonator coated with SWNTs using a conductive epoxy, which selectively detects the qualitative presence of several gases (NH_3, CO, Ar, N_2 and O_2) due to changes in the dielectric constant and shifts in the resonant frequency. However, these resonant-circuit sensors are less sensitive than those that use CNT-FET devices [63]. Modi et al. [38] developed a gas ionization sensor made of MWNTs that can selectively detect a variety of gases (He_2, Ar, Ni_2, O_2, CO_2 and NH_3). This sensor was based on the breakdown voltage (unique for each gas at constant temperature and pressure) of each gas measured in the very high nonlinear electric field created near the MWNT tips. This breakdown voltage causes the formation of a corona of highly ionized gas, which allows for a self-sustaining inter-electrode discharge at relatively low voltages. This nanosensor detects concentrations in the 10^{-7} to 10^{-1} mol/L range. Wei et al. [64] demonstrated a gas sensor depositing CNT bundles onto a piezoelectric quartz crystal. This sensor detected CO, NO_2, H_2 and N_2 by detecting changes in oscillation frequency and was more effective at higher temperatures (200 °C). Penza et al. [65] developed a surface acoustic wave (SAW) sensor coated with SWNTs and MWNTs (depositing the CNTs by a spray-painting method onto the ST-X quartz substrates) and used it to detect volatile organic compounds (VOCs) such as ethanol, ethylacetate and toluene by measuring the downshift in the resonance frequency of the SAW. The selectivity of the VOCs to be detected can be controlled by the type of organic solvent used to disperse the CNTs onto the SAW sensor. With this device, limits of detection of 1 ppm for ethanol and toluene are easily reached.

As with nanoparticles, carbon nanotubes can be easily functionalised with molecules that interact specifically with target analytes. The procedure involves first adsorbing a polymer onto the surface of the nanotube. The non-covalent functionalization of the CNT with the polymer keeps the electronic structure of the CNT intact. Also, the nanotube is protected against non-specific interactions with unwanted analytes and specific molecules can be covalently attached to the polymer in order to interact specifically with the target analytes. In this way, different types of sensors based on molecular recognition interactions can be developed. These types of interactions allow for the development of nanosensors that are highly selective and sensitive. Moreover, the traditional problem of lack of signal when the target analyte interacts with the recognition molecule is overcome. The presence of the analyte is enough to induce an input or withdrawal of electrical charges that produce changes in the conductivity of the nanotubes. Directly detecting the analytes, i.e. without using reagents or markers is a significant advantage over other types of sensors. Finally, electrical detection allows for simple and inexpensive instrumentation, which improves the portability of these type of devices.

In this way, Chen et al. [66] used a noncovalent functionalized FET based on SWNTs for selectively recognising target proteins in solution. Azanian et al. [67] immobilized glucose oxidase on SWNTs and enhanced the catalytic signal by more than one order of magnitude compared to that of an activated macro-carbon electrode. Zhao et al. [68] worked with horseradish peroxidase and Sotiropoulou et al. [69] worked with enzymes. Barone et al. [70] developed a device for β-D-glucose sensing in solution-phase. They also showed two distinct mechanisms of signal transduction: fluorescence and charge transfer.

Nanowires other than CNTs have also been used to build nanosensing devices, though to a lesser extent than CNTs. Although there are many types of nanowires, most of them have a semiconductor character. The manufacturing processes are extremely diverse and include, for example, alternating current electrodeposition [71–73], laser ablation [74], thermal evaporation [75] and CVD [76]. All the sensing devices we have reviewed that use nanowires are of the FET-type (i.e. they measure the change in the electrical conductance of the nanowire at a given bias and gate potentials), and none of them use functionalized nanowires. Favier et al. [77–79] synthesised Mo and Pd metal nanowires using an electrochemical method. They then connected an array of these nanowires with two Ag contacts and used the device to detect H_2 in H_2/N_2 mixtures with a limit of detection of 0.5% H_2. Wang et al. [80] found that a thin-film sensor made of SnO_2 nanowires changed its resistance when it was exposed to several gaseous species (CO, ethanol and H_2), which makes it suitable for sensing purposes. Kolmakov et al. [71] made a sensor with a single SnO_2 nanowire that qualitatively changed resistance in the presence of O_2. These authors claimed that with this strategy it would be possible to manufacture a large array of individualized nanowires (either by manipulating their material composition or the way in which each nanowire is functionalized) to create a parallel sensing device that is able to detect many different species and mimic complex functions such as olfaction. Li et al. [81,82] studied the capabilities of In_2O_3 nanowires in sensing devices and detected a concentration of NH_3 of 0.02%, or 2 ppm of NO_2. These authors also claimed that there were also substantial shifts in the threshold voltage, which can be used to distinguish between gas species. Zhang et al. [74,83] developed a FET also using multiple In_2O_3 nanowires (the sensing part) attached to Ti/Au electrodes. They used it to selectively detect ppb of NO_2 (with a detection limit of 20 ppb), even in the presence of other chemical substances such as NH_3, O_2, CO and H_2, without having to functionalise the nanowire. Silicon nanowires also have promising features for use in chemical sensors, even in aqueous solutions [84], though they are difficult to functionalise. Bundles of etched silicon nanowires (using two silver glue electrodes separated by 5 mm) have been successfully used [85] to qualitatively detect

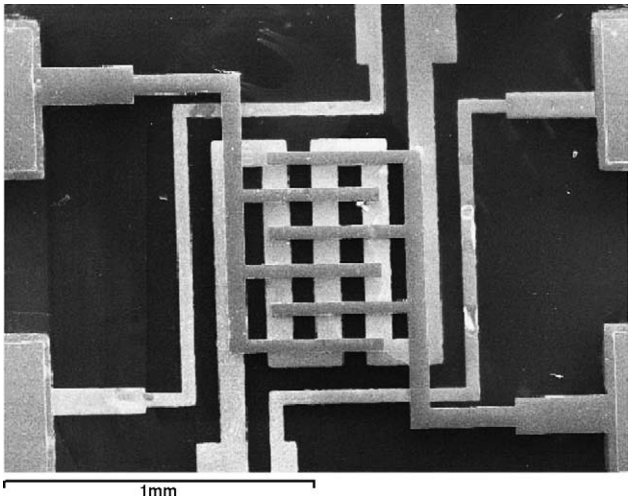

Fig. 4. SEM image of the Pt interdigitating electrodes embedded with ZnO nanowires (Reprinted with permission from Appl. Phys. Lett. 84 3654–3656 © 2004).

NH_3 and water vapour. Wan et al. [86] built an ethanol sensor device with Pt interdigitating electrodes embedded with ZnO nanowires. This device was able to qualitative change its electrical resistance with the presence of 1 ppm of ethanol. Since ZnO nanowires can be massively synthesised by thermal evaporation, the authors claimed that this could open the door to the mass production of sensing devices (Fig. 4).

Murray et al. [87] used silver mesowires prepared by electrochemical step edge decoration to investigate their behaviour as sensing devices in the presence of several gases. They found that the mesowires adequately detected qualitative amounts of NH_3, that they can also be useful for detecting several amines (but with a slower response), and that their resistance does not change when they are exposed to CO, O_2, Ar, H_2O or hydrocarbons. Nanowires have also been synthesized from conducting polymers. Polyaniline/poly(ethylene oxide) (PANI/PEO) nanowires have also been used (deposited on lithographically defined microelectrodes) to design a NH_3 sensor. The similarity of the coordinative roles of nitrogen atoms in PANI and NH_3 gives rise to the affinity of the polymer for NH_3 [12].

4. Sensors based on nanostructures embedded in bulk material

Bulk nanostructured materials are solids with a nanosized microstructure. Their basic units are usually nanoparticles. Several properties of nanoparticles are useful for applications in electrochemical sensors and biosensors but their catalytic behaviour is one of the most important. The high ratio of surface atoms with free valences to the total atoms has led to the catalytic activity of nanostructured material being used in electrochemical reactions. The catalytic properties of nanoparticles could decrease the overpotentials of electrochemical reactions and even provide reversibility of redox reactions, which are irreversible at bulk metal electrodes [88]. Multilayers of conductive nanoparticles assembled on electrode surfaces produce a high porous surface with a controlled microenvironment. These structures could be thought of as assemblies of nanoelectrodes with controllable areas.

Platinum nanoparticles supported on materials such as porous carbon or noble metals such as gold are reported to be relevant in the design of gas diffusion electrodes [89]. A practical example is provided by Chiou et al., who reported an electrode for SO_2 sensing based on gold nanoparticles with a diameter of 21 nm on the surface of carbon [90]. Gold particles catalyze the electrochemical oxidation of SO_2 when the gas diffuses through the porous working electrode.

Resistors are the basis for one of the simplest types of sensors. The electrical resistance of resistive sensors depends on the chemical species to which they are exposed. When chemiresistors are made of nanoparticles or nanotubes integrated into different organic matrices, their interaction with gases can be tailored and the selectivity and sensitivity of the sensor can be modulated. In this way, NH_3 has been detected with Pd nanoparticles structured into a poly(*p*-xylylene) film [91]. Also, low polarity vapours have been detected with gold nanoparticles placed between poly(propyleneimine) dendrimers. This resistor is able to detect toluene at 1 ppm (v/v) [92].

The high surface area of nanoparticles is suitable for immobilising molecules, polymers or biomaterial coatings that allow the generation of composite materials with tunable surface properties. For example, modifying metal nanoparticles with predesigned receptor units and assembling them on surfaces could lead to new electrochemical sensors with tailored specificities. As an example, Shipway et al. [93] developed a group of sensors using multilayers of gold nanoparticles crosslinked by molecular host components. Fig. 5 shows the general method for constructing the multilayer Au-nanoparticle structures. First, the conductive glass support is functionalized with a thin film of 3-(aminopropyl)siloxane. The siloxane is bonded to the glass surface through the OH groups of the glass (the surface of which is previously scrupulously cleaned, usually by oxidative cleaning in acidic solution, to ensure the maximum number of exposed surface OH groups). This reaction provides a positively charged surface. The electrostatic interaction between the functionalized glass surface and the negatively charged citrate-stabilized Au-nanoparticles (about 12 nm in diameter) yields the first layer of Au nanoparticles. Subsequently treating the negatively charged interface with the positively charged molecular host components provides suitable association and leaves the surface ready to interact with the next layer of citrate-shielded Au-nanoparticle. The alternate procedure provides architecture of the desired thickness.

The different crosslinkers can have different properties. For example, they can act as p-acceptor molecules that are able to form *p*-donor–acceptor complexes. In this way, the association of electroactive *p*-donor substrates to the *p*-acceptor receptor sites, together with the three-dimensional conductivity of the nanoparticle architecture, enables electrochemical sensing by the substrates. Using bipyridinium cyclophanes as a crosslinking host molecule, Shipway et al. [93] were able to detect hydroquinone at concentrations of 1 mM.

The sensing mode of the devices based on modified nanoparticles is usually voltammetric. Efficiency is therefore related to

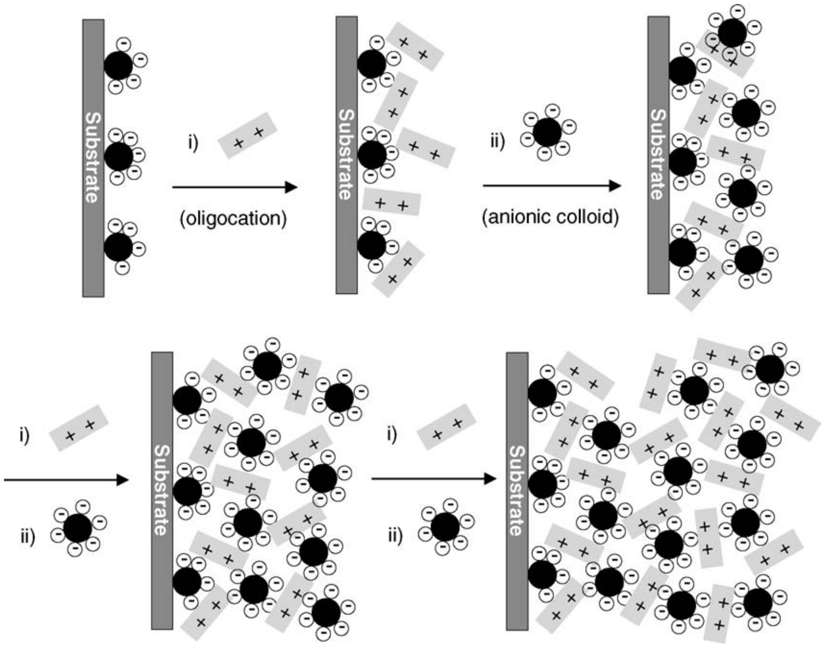

Fig. 5. Construction of multilayer Au-nanoparticle structures based on electrostatic interactions. The first layer of Au-nanoparticles is attached to the glass-siloxane surface. The various layers are then constructed using a positively charged cross-linker (step (i) in the upper figure). Cross-linkers may be anything from a small molecule (e.g. C_{60}) to other nanoparticles, but they must bear multiple charges. (Reprinted with permission from A.N. Shipway, E. Katz, I. Willner, Chem. Phys. Chem. 1 18–52 © 2000).

the concentration of the analyte at the surface of the electrode. Moreover, the sensors are limited to the redox-active analytes. The deposition of the nanoparticles linked to receptors on the ion-sensitive field effect transistors in a way that is similar to that above for the NanoFETS and allows the detection of charged species. Enzymes can also be linked to nanoparticles to produce new bioelectrochemical systems. Xiao et al. [94] reported biocatalytic electrodes prepared by co-deposition of redox enzymes and Au nanoparticles on electrode supports. The conducting properties of metal nanoparticles are used in this way for the electrical wiring of redox enzymes to the electrodes.

Carbon nanotubes have also been used for the construction of different types of electrodes. Zhao et al. [95] built a CNT electrode using a powder microelectrode method. Then using a platinum wire counter electrode and a Ag/AgCl reference electrode they detected nitrite in solution with a detection limit of 8 μM. Ye et al. [96] functionalized CNTs with hemin (iron protoporphyrin IX) and connected them to a glassy carbon electrode. This (working) electrode, together with a platinum counter electrode and a Ag/AgCl reference electrode, formed the basis for voltammetric measurements. With this device they qualitatively catalyzed the reduction of hydrogen peroxide and oxygen. He et al. [97] developed a microelectrode based on MWNTs that exhibited a strong catalytic effect on the electrochemical oxidation of CO in solution. With this device, the linear working range was from 0.72 to 52 μg/ml and the detection limit was 0.60 μg/ml.

In summary, the exclusive properties of nanoparticles improve the performance of standard electrochemical methods. High current flows and sensitivities are attainable thanks to the conduction capacities combined with high surface areas. Simple and highly-selective electroanalytical procedures can also be achieved by proper funtionalisation of nanoparticles. Finally, stable nanoparticles can substitute amplifying labels of limited stability, such as enzymes or liposomes, with equivalent or improved sensitivities [88].

5. Sensors based on porous silicon

When a silicon wafer is placed as the anode of an electrochemical cell and a current is passed through it in the presence of an ethanolic solution of fluorhydric acid, some Si atoms are dissolved and the remaining film material, similar to a sponge, is known as porous silicon. The porous material is a complicated network of silicon threads, each with a thickness in the 2–5 nm range. The dimensions of the pores range from a few nanometers to several microns. The result is a semiconductor material that displays an internal surface area-to-volume ratio of up to 500 m^2/cm^3. The extremely tiny pores give the material a strong luminescence at room temperature. It is generally agreed that the light emission is due to quantum confinement effects, i.e. the spatial confinement of electron-hole pairs in nanometer-scale silicon particles that remain after etching [98]. Light emission takes place mainly in the visible region of the electromagnetic spectrum. This emission has the unique property that the wavelength of the emitted light depends on the porosity of the material. For example, a highly porous sample (>70% porosity) will emit at shorter wavelengths with green/blue light, while a less porous sample (40%) will emit at longer wavelengths with red light. The luminescence of *n*-type porous silicon, for instance, is altered when molecules are incorporated into the porous layer. This property has led to the design of gas sensors whose qualitative

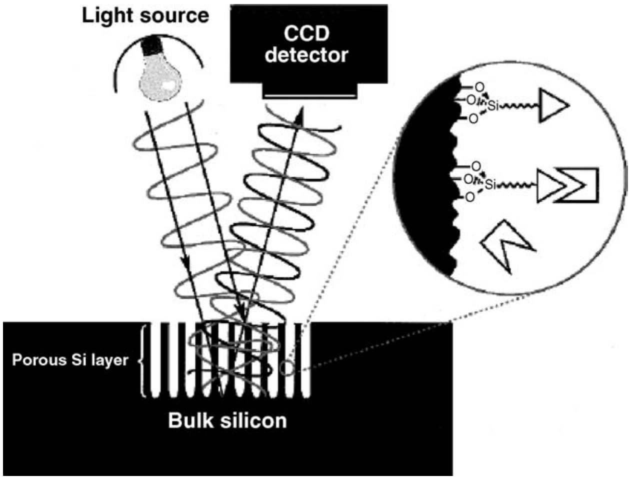

Fig. 6. Schematic representation of Fabry-Perot fringes obtained as an interference pattern when the light is reflected at the top and bottom of the porous silicon layer. The interference spectrum is sensitive to the refractive index of the porous silicon matrix. This changes upon reaction with analytes. (Reprinted with permission from V.S.Y. Lin, K. Motesharei, K.P.S. Dancil, M.J. Sailor, M.R. Ghadiri, Science 278 840–843 © 1997 AAAS).

response can be monitored by visually observing a change in colour. In most nanosensors, porous silicon functions as both matrix and transducer.

Thin films of porous silicon also display well-resolved Fabry-Perot fringes in their reflectometric interference spectrum (Fig. 6). When white light is reflected at the top and bottom of the porous silicon layer, the resulting interference pattern is related to the thickness and the refractive index of the film. The refractive index of the porous silicon changes when specific analytes of the sample are recognised by molecules that have previously been linked to the high surface area of the pores. A shift in the interference pattern can therefore be detected. This property has been used to detect small organic molecules at pico- and femtomolar analyte concentrations. The sensor is also highly effective for detecting single and multilayered molecular assemblies [99].

A similar phenomenon is used by Steinem et al. [100]. The catalysed degradation of porous silicon by certain transition metal complexes is the basis for a new sensor principle in which the porous layer serves as matrix, transducer and signal amplification stage. Reflectance spectroscopy is used to monitor the degradation of the pores that takes place when the concentration of the metallic complex increases within the pore. To amplify the presence of the metal ions, receptors that recognize and bind to the metal-complexes are immobilized within the porous matrix (Fig. 7). Contaminants, such as toxins or metallic ions in water samples, are detected by the blue shift in the Fabry-Perot fringe pattern and quick effective optical thickness decay.

6. Nanomechanical sensors

Mass sensitive transducers are the basis of the different types of mechanical sensors such as quartz crystal microbalances and surface acoustic wave devices [101]. The basic principle is that the resonance frequency changes when a mass is placed on the resonator. Although many applications are available, it is difficult to significantly improve their quality parameters at the macroscopic size. This can only be done when cantilever resonators are reduced to nanosize dimensions because the resonance frequency is proportional to the inverse of the linear dimension of the cantilever. Frequencies in the range of MHz are achieved in this way with cantilever sizes in the range of μm, and frequencies in the range of GHz can only be achieved at the nm scale. The change in the resonance frequency of the cantilever is proportional to the mass on the resonator. Nanosized cantilevers can therefore detect up to attograms, but the aim is to detect the mass of individual molecules.

As an example, Lavrik et al. [102] obtained gold-coated silicon cantilevers that measured 2–6 μm long, 50–100 nm thick, and had resonance frequencies in the 1 to 6 MHz range (Fig. 8). A total mass of a few femtograms of 11-mercaptoundecanoic acid vapours that was chemisorbed on the surface of gold-coated cantilevers was monitored in air (Fig. 9).

Single-walled carbon nanotubes embedded in an epoxy resin have also been used as mechanical sensors because the position of the D^* Raman band of SWNTs strongly depends on the strain transferred from the matrix to the SWNTs [68]. This sensor was used to measure the stress field around an embedded glass fibre in a polymer matrix.

7. Self-assembled nanostructures

The nanostructures explained thus far have been developed following the top-down approach, i.e. starting with large-scale objects and gradually reducing its dimensions. Self-assembling tries to develop the nano and microstructures following the bottom-up procedure, i.e. from simple molecules to more

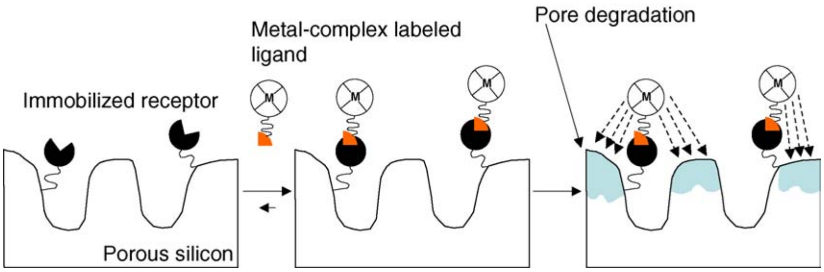

Fig. 7. Porous silicon corrosion enhancement via molecular recognition of a reactive metal complex (M) labelled ligand by a receptor immobilized on p-type porous silicon. Each metal complex can induce degradation of the porous silicon that can be detected in the reflectance spectra (www.scieng.flinders.edu.au/cpes/people/voelcker_n/html_files/biosensors.html).

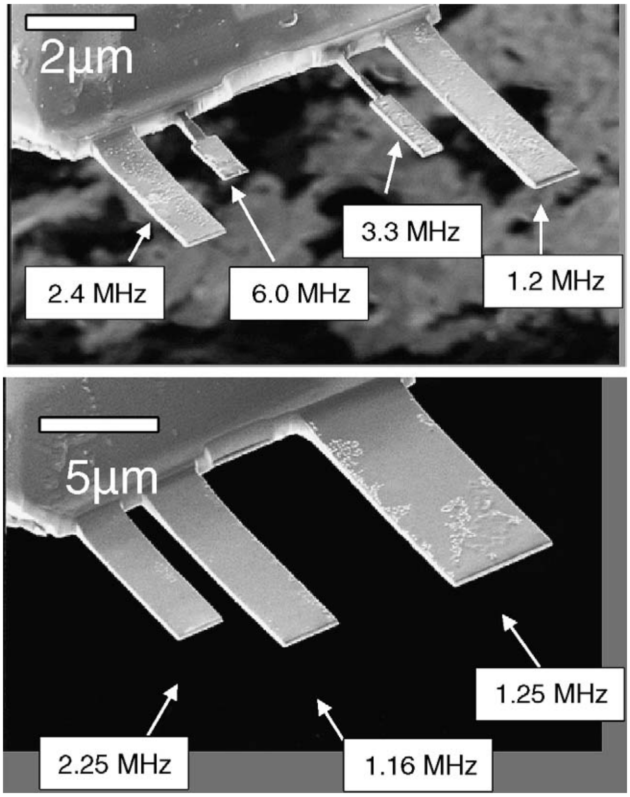

Fig. 8. Ion scanning micrograph of gold-coated silicon microcantilevers. Approximate values of the resonance frequencies are indicated for each cantilever (reprinted with permission from N.V. Lavrik, P.G. Datskosa, Appl. Phys. Lett. 82 2697–2699 © 2003).

complicated systems [30,103]. Of the self-assembled structures, those using liposomes, polymerised lipid vesicles or pseudo-cellular membranes, are the most widely studied [104]. In 1997 Cornell et al. [105,106] reported a bionanosensor that has been commercialised under the name of ion channel switch, ICS^{TM}. This sensor is made up of a set of biomolecules that, mimicking nature very much, combine in such a way that the biochemical detection of an analyte is converted into an electrical signal. The biosensor is amperometric. An Au-coated support is the ionic conductor that is in contact with a reservoir to which sodium ions can only gain access through molecular channels made of gramicidin molecules. The gold electrode and the reservoir are isolated by a lipid bilayer membrane that contains gramicidin molecules. When the two dimers of the gramicidin coincide, the channel is activated and the sodium ions can flow through it, gain access to the reservoir and change the conductance of the sensor. The sensor works by relating the presence of the analyte to the alignment of the molecular channels and the presence of Na$^+$ ions into the reservoir.

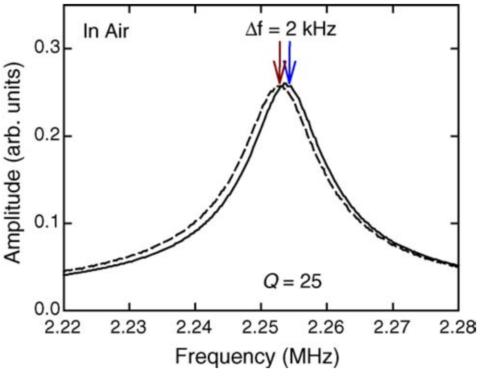

Fig. 9. The adsorption of 5.5 fg of thiol containing molecules under ambient conditions on the Au microcantilever produced a frequency shift in the cantilever resonance (reprinted with permission from N.V. Lavrik, P.G. Datskosa, Appl. Phys. Lett. 82, 2697–2699 © 2003).

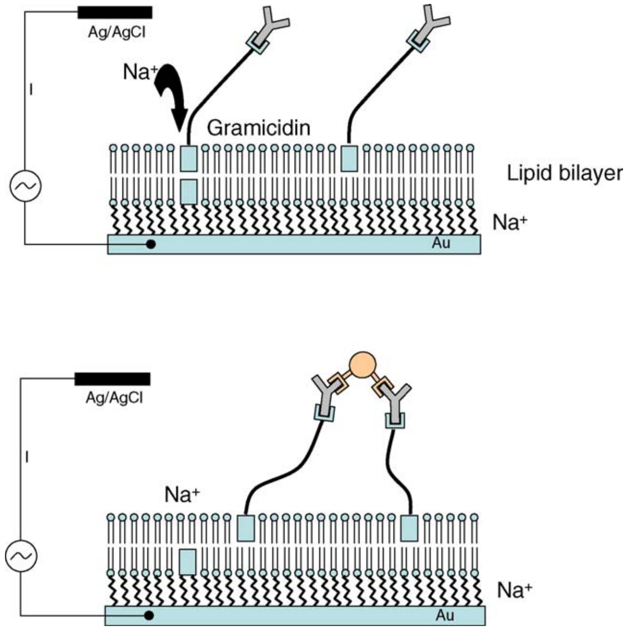

Fig. 10. Scheme of the ion channel switch biosensor. Upper figure, the ion channel is on. Lower figure, the analyte prevents the dimers of the gramicidin from coinciding and the channel is off.

Fig. 10 shows the principle of the ion channel switch biosensor. A bilayer of glycerophospholipids (containing a polar region and two non-polar hydrocarbon tails of fatty acids) self assembles spontaneously in aqueous media. The lower layer is tethered to the gold support by means of thiol groups. The gramicidin (a peptide, with alternating D and L amino acids) is also tethered to the gold support. In lipid bilayer membranes, gramicidin dimerizes and folds as a helix in such a way that the outer surface of the gramicidin dimer, which interacts with the core of the lipid bilayer, is hydrophobic, while ions pass through the more polar inner part of the helix. The two monomers of the gramicidin must coincide to activate the channel. Receptors, such as antibodies, are linked to the membrane and to the upper dimer of the gramicidin by means of linker proteins such as streptavidin and biotin. The detection mechanism works when the target molecule is bound to the receptor fragment. In this case, the population of conduction ion channels pairs within the tethered membrane is altered and this changes the membrane conduction. With this biosensor, picomolar concentrations of proteins have been detected [107]. As well as being sensitive, the sensor is flexible enough to work with many types of receptors. It can therefore be used in a variety of fields ranging from biomedical analysis, the detection of environmental problems or food control.

8. Receptor-ligand nanoarrays

Going a further step forward of the microarray technology [108], nanoarrays are being developed based on the interaction between different types of receptors and ligands such as proteins or nucleic acids. Approximately 400 nanoarray spots can be placed in the same area as a traditional microarray spot. DNA biosensors are based on the immobilisation of a single-stranded nucleic acid sequence onto surface for hybridisation with an unknown target sequence. This DNA hybridisation typically occurs directly on the surface of an active signal transducer that produces a measurable signal, often in real time [109]. Depending on the transducer, DNA biosensors are grouped in evanescent or acoustic wave sensors, electrochemical sensors and optical sensors. Evanescent and acoustic wave sensors indirectly detect DNA hybridization by measuring physical properties changes such as the refractive index. Electrochemical biosensors measure current or resistance changes caused by the hybridisation of DNA probe molecules attached to an electrically active surface. Optic DNA biosensors measure fluorescence changes of DNA probes such as molecular beacons. Molecular beacons are hairspin-shaped oligonucleotides probes containing a sequence complementary to the target that is flanked by self-complementary termini, and carries a fluorophore and a quencher at the 3′- and 5′-ends [110]. In the absence of the target, these molecules form closed stem-loop structures in which the fluorophore and quencher are in close proximity, which quenches the fluorescence. In the presence of the target, the molecular beacon forms a complex with its target, which separates the fluorophore from the quencher. This gives rise to a fluorescence increase that quantitatively signals the presence of the target.

DNA biosensors have been applied in environmental analysis for the quantification of genes associated to numerous environmentally prominent pathogens [111], including *P. aerugniosa* [112], *Mycobacterium tuberculosis* [113] and *Rhodococcus equi* [114]. Molecular beacons have been also applied to pathogen detection [115–119] but there is little literature published regarding with environmental applications [120,121]. Harms et al. have recently applied molecular beacons to quantify nitrifying bacterial in a municipal wastewater treatment plant [121].

9. Conclusions

In this paper, we have discussed several types of existing nanosensors and their application in the field of environmental analysis, highlighting the relationship between the property monitored and the type of nanomaterial used. Although fundamental developments in the nanoscience field are still appearing, the well known effects arising only when the size of the structures is reduced are being applied to develop new sensing devices.

Among all the reviewed types of nanostructures, nanoparticles and carbon nanotubes probably stand out. Most of the reviewed nanostructures have successfully shown a great potential for being used in nanosensors, but the versatility and high applicability of nanoparticles and carbon nanotubes makes them clear candidates to be further used in nanosensors.

Acknowledgements

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