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Current Status of Platinum Based Nanoparticles: Physicochemical Properties and Selected Applications – A Review

Platinum-based nanoparticles in electrochemistry, photochemistry and sensors

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The present article reviews the synthesis routes and applications of platinum-based nanoparticles in emerging fields such as energy harvesting, health care applications and sensors. Increasingly, more useful, novel and multifunctional materials are needed with fewer side effects. This article provides an overview of Pt-based nanoparticles along with recent applications in electrochemistry, photochemistry, biosensors and gas sensors. In particular, platinum dioxide (Adams' catalyst) has been used in many chemical reactions including hydrogenation, oxidation and reduction.

1. Introduction

An enormous number of metal oxide nanoparticles are utilised and appreciated for their unique properties and applications in the disciplines of nanoscience. Due to their distinct behaviour PtO_2 nanoparticles have significant catalytic activity. They were first prepared by Adams and are labelled Adams' catalyst (1). Adams' catalyst, or PtO_2, has been prepared mostly by colloidal techniques. The metal precursor produces an enhanced form of Pt catalyst after reduction with hydrogen. Finally there is the formation of stable Pt(0) in the form of nanoparticles. This catalyst is used for further applications in chemical reactions.

PtO_2 has two different stable states: α-PtO_2 and β-PtO_2; α-PtO_2 has a hexagonal system at ambient pressure and β-PtO_2 has an orthorhombic system at high pressure (2). The β-PtO_2 displays more than one structure due to the presence of a larger amount of Pt^{3+} ions leading to the higher volume of β-PtO_2 and a smaller amount of oxygen. Pt^{4+} ions exhibit a tetragonal rutile structure in β-PtO_2 due to the maximum number of coulombic communications. Additionally, Pt^{3+} ions display an orthorhombic structure in β-PtO_2 due to the occurrence of high cationic interactions (3). Nanosized PtO_2 particles have revealed identical physical and chemical properties. Nano platina has been used to prepare novel materials for magnetic, high conductance, optical and thermal requirements for various specifications (4). Obviously, nanomaterials are currently of great interest, due to their potential physicochemical properties such as optoelectronic, electrical conductivity, mechanical strength, excellent magnetic and thermal properties. Materials having such properties might be introduced for various applications such as photocatalytic degradation, electrochemistry and biosensor applications and these factors are briefly described in this review.

1.1 Platinum Nanoparticles in Nanomaterials

Pt nanoparticles incorporated with tin(IV) oxide nanomaterials were investigated for their electrocatalytic properties through the

electrochemical oxygen reduction reaction (ORR) (Pt/SnO_2 *vs*. glassy carbon electrode). Electrochemical assessment showed that the Pt loaded electrode exhibited good activity for the ORR due to its high surface area (5). Pt supported on carbon having a large surface area is used as the cathode in polymer electrolyte fuel cells (PEFCs). However, Pt/SnO_2 nanowires have produced higher ORR activity than Pt/C, due to the low surface area of Pt/C as a reference catalyst in the ORR (6). Recently, galvanic exchange reactions have been used to synthesise different types of nanomaterials such as alloys, bimetallic nanoparticles and noble metals like Pt, gold and palladium with heterostructural morphology (7). Cobalt nanoparticles have acted as structure-inducing agents to achieve various kinds of morphology in metals and metal oxide nanomaterials including nanotubes, nanorods, nanowires and nanospheres (8).

Novel Pt-based nanoparticles having excellent physicochemical properties have been prepared with metals such as Pd, lead and iron. Pt nanoparticles were combined with Pd to form a 'dandelion like' surface morphology of core-shell nanoparticles. These Pt@Pd core-shell nanoparticles have been used as a highly active catalyst for olefin reduction reactions (9). The Pt@Pd core-shell nanoparticles have also been encapsulated with reduced graphene oxide (rGO) by microwave techniques. The resulting catalyst (Pt@Pd/rGO) had good physicochemical properties and has been used as a catalyst for dehalogenation in aromatic reactions through reduction of olefins with 98% improvement in yield and selectivity. The catalyst was further reusable more than five times in dehalogenation and reduction reactions of olefins. Noble metal-based nanoparticles such as Au@Cu, Au@Pd and Pd@Cu have comparatively good catalytic activity due to their size, surface area and morphology (10) and have been used as catalysts in organic reactions (11, 12). Pt nanoparticles incorporated into other materials have exhibited potential catalytic improvements (13) and can be easily synthesised through physical methods. There has been much focus on graphene oxide (GO) and rGO based core-shell nanomaterials including metal/GO and metal/rGO catalysts for methanol oxidation, metal salt reduction and electrocatalysis, due to their high activity, large surface area, superior electrical conductivity, high stability and recyclability (14). The modification of graphene into GO and rGO through oxidative exfoliation can lead to inadequate surface functionality due to its hydrophobic nature. Because GO and rGO are hydrophilic in nature, the stability of core-shell nanomaterials is maintained. In Pt@Pd/rGO core-shell nanoparticles, a tendency for dehalogenation reactions has been observed with dehalogenation reaction following the order F << Cl < Br < I (15).

1.2 Structural Properties

PtO_2 structures were established as tetragonal PtO, Pt_3O_4, Pt_5O_6, Pt_3O_8 and PtO_2 as determined by X-ray diffraction (XRD) spectroscopy (16). The structural elucidation of PtO_2 as β-PtO_2 (cadmium iodide type, space group Pnmm) (17) and α-PtO_2 was confirmed to be a hexagonal close packed structure (CdI_2 type, space group P-3m1) (18). XRD was used to determine the lattice parameter of α-PtO_2 film: a = 3.113 ångström (Å), c = 4.342 Å and lattice parameter of α-PtO_2 powder: a = 3.10 Å and c = 4.29–4.41 Å (19). β'-PtO_2 has a rutile type structure (space group P42/mnm) (3). PtO_2 has an octahedral structure, formed from amalgamation of Pt in six-fold axis and oxygen in three-fold axis. The oxidation state of PtO_2 has been found to be +4 and PtO is considered to be +2 which implies a GeS-type structure, even though the Pt atom was six-fold. The Pt-Pt bond length in Pt_2 was found to be 2.33 Å (20). Vacancy produces magnetism from oxide combined materials such as calcium oxide (21), zinc oxide (22), magnesium oxide (23), titanium dioxide (24), tin(IV) oxide (25) and hafnium(IV) oxide (26) to group III-nitrides (for example, gallium nitride and boron nitride) (27) and magnetic behaviour has also been established in diamond, graphite and graphene (28). Generally, oxides and nitrides of Pt occupy 2p orbitals or an open d shell with cation/anion vacancies, therefore PtO_2 (β-PtO_2) has vacancies which stimulate intrinsic magnetism due to the occurrence of the β phase.

The β-PtO_2 structure was found to be similar to the calcium chloride type crystal structure and to the TiO_2 type crystal structure with distortion (29). The Vienna *Ab initio* Simulation Package (VASP) was used to calculate the vacancy sites in the crystal system through plane wave and projector augmented wave method (PAW) potential. The plane wave energy was more than 600 electron volts (eV) (30). Coulomb repulsion (U_{eff}) plays an important role in band gap energy and β-PtO_2 has higher resistivity compared to α-PtO_2 with resistivity values of 10^6 Ω cm and 10^4 Ω cm respectively (31), however two different oxygen vacancies corresponding to $PtO_{1.958}$ and $PtO_{1.986}$ were δ = 0.042 and δ = 0.014 respectively. The energy

value between Fermi levels is an unoccupied state at approximately 31 megaelectron volts (meV) and clearly depicts the transformation of electrons from one system into another vacancy state of a and b crystal system (32). There are numbers of planes of α-PtO_2 with area identified using the Joint Committee on Powder Diffraction Standards (JCPDS) card, with the planes (0001) and (1010) found to be more stable (33). When excited, the oxygen vacancy in α-PtO_2 (0001) and changes in surface area lead to distortion structure as shown in **Figure 1(a)**, **Figure 1(b)** and **Figure 1(c)**.

1.3 Chemical Reactivity

Heterogeneous catalysts have higher catalytic activity than homogeneous catalysts due to the presence of a large surface area. Additionally, sintered particles of PtO_2 possess different activation energies of 3.77 eV to Pt (bulk material) and –2.05 eV to Pt (gas), which depend upon the size of the nanoparticles. High sintering temperatures greater than 427°C provide more entropic driving force for vaporisation due to the low pressure of unstable particles (34). In recent research, the reaction of oxygen on metals such as cobalt, nickel, zinc, copper, Pt and Pd has been used to reduce atmospheric pollution. PtO_2 increases the chemical reactivity of $CoO/CoAl_2O_4$. The percentage of three capping materials has shown good reactivity in $CoO/CoAl_2O_4$, (CoO + 1.0% PtO_2)/$CoAl_2O_4$ and (CoO + 1.0% Rh_2O_3)/$CoAl_2O_4$, whereas time of reduction reaction was reduced by the addition of PtO_2 (35). PtO_2 has been applied to a wide range of chemical reactions such as hydrosilylation of olefins (alkenes) (36), defined as the addition of silicon and hydrogen on an unsaturated double bond (C=C) or triple bond (C≡C) (37). PtO_2 as a heterogeneous catalyst for the hydrosilylation reaction can be easily removed compared to homogeneous catalysts. Homogeneous catalytic reactivity was first carried out by Karstedt using H_2PtCl_6 and Pt $(PPh_3)_4$ after which it was labelled as Karstedt's catalyst (38). The hydrosilylation reaction was studied using proton nuclear magnetic resonance (^{1}H-NMR) spectroscopy with the ratio of the Si-H singlet of silane at 4.7 ppm and the Si-CH_3 singlet of the product at 0.5 ppm (39).

1.4 Effects of Temperature and Air

There are many factors affecting the chemical reaction of metal oxides, such as atmospheric oxygen, the presence of impurities and time. Temperature is one of the most important factors and PtO_2 dissociates at a temperature of around 427°C (3). At 400°C, PtO_2 decomposes to Pt and O_2. A mixture of PtO_2 and carbon in helium decomposed at 550°C, as determined by differential thermal analysis (DTA), the same as PtO_2/He. When heated to 750°C Pt oxide lost weight as determined by thermogravimetric analysis (TGA), whereas Pt/C produced an exothermic reaction in the presence of He and air at high temperature enhanced by oxygen (40). Normally, transition metals easily corrode during oxidation reactions due to the presence of atmospheric oxygen in air. In a similar way Pt undergoes structural changes at the surface in the presence of air at pressure 0.025 bar to 1000 bar (41, 42). Hence, Pt metal can be treated in air or oxygen at high temperature of 400°C to 500°C to convert directly metal into gas using critical temperature which leaves the vicinity of the

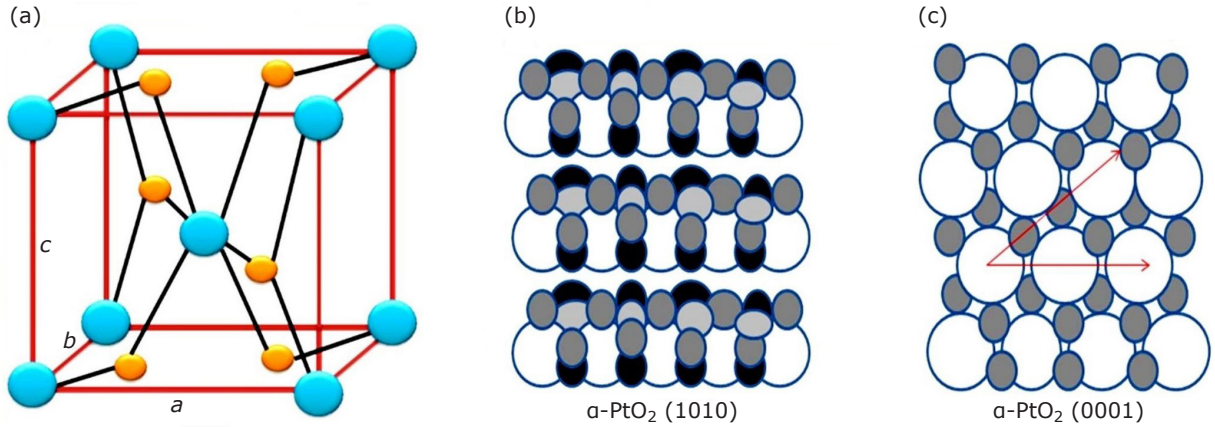


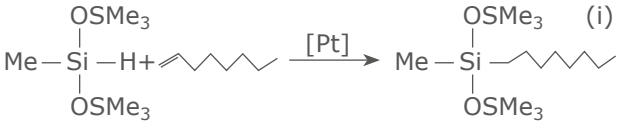
Fig. 1. (a) Crystal structure of PtO_2; (b) α-PtO_2 (1010); (c) α-PtO_2 (0001)

metal (43). In the presence of air with Na_2O-PtO_2 composition a monoclinic cell, space group C'2/c, with a = 5.411 Å, b = 9.386 Å and β = 99°39′ and orthorhombic and monoclinic cell structure with general formula A_2BO_3 were determined by XRD spectroscopy (44).

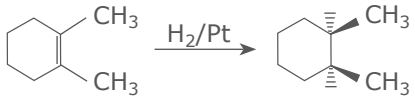
2. Applications

2.1 Effective Catalyst in Organic Reactions

Pt is a transition metal with heterogeneous catalytic activity for specific chemical reactions such as removal of hydrogen, transfer of hydrogen and addition of oxygen, as shown in Equations (i)–(iii). In addition, Pt nanoparticles have high surface area and well defined catalytic performance (39). The transition metals Ni and Pd have similar characteristics to Pt nanoparticles. 0.05–2 wt% Pt nanoparticles were mixed with mesoporous silicas (SBA-15 and KIT-6) and aqueous ammonium tetrachloroplatinate(II) and calcined at 500°C to achieve Pt nanoparticles (45, 46). The same size nanoparticles were produced with different crystal systems due to the presence of catalyst to modify their structure (46). The catalytic activities of reaction sites for nanoparticles are dependent on both shape and crystalline facets in different orientations. Some facets exhibit higher catalytic activity than others, due to the involvement of oxygen on the Pt(100) plane and reduction on the Pt(111) plane (47, 48). Pt nanoparticles have been used as a catalyst in reaction with γ-Al_2O_3 to form nanoparticles of diameter around 0.2–0.8 nm before the elimination of polymer in O_2 at 375°C following the deposition and annealing process, as determined by scanning transmission electron microscopy (STEM) and extended X-ray absorption fine structure (EXAFS) (46). Supported Pt nanoparticles exhibit enhanced catalytic properties in the electro-oxidation of methanol due to increase in surface area of the Pt catalyst, which undergoes annealing to form smaller nanoparticles (49–51).



(i)



(ii)

$$CH_3CH = CHCH_3 + H_2 \xrightarrow[Pt/C]{} CH_3CH_2CH_2CH_3 \quad \text{(iii)}$$

Supported Pt nanomaterials have been used in heterogeneous catalysts, with increased catalytic activity in the oxide phase (18). γ-Alumina doped with 1.5 wt% Pt is susceptible to poisoning by reactants such as nitric oxide, sulfur dioxide and hydrocarbons that could be eliminated at high temperature. The Pt nanoparticles were used as material dopant with Al_2O_3 for preparation of 2-propanol by an oxidation route, while the same kind of doped substance has produced conversion of more than 80% for the formation of acetone, carbon dioxide and water (46, 52, 53).

2.2 Photocatalysts

Generally, photocatalyst materials are considered to retain their own lifetime efficiently. Photocatalytic degradation of alcohols was studied using a PtO_2/TiO_2 nanocomposite (54–56). Transition metals ensure high electron capture between the conduction and valence band gap for photocatalytic performance (57). PtO_2 has been used to improve the photocatalytic activity of Ti-based materials. With increased Pt content of 1 wt% to 2 wt% the degradation was 61% and 51%, respectively. PtO_2 nanoparticles instead of Pt improved the degradation of phenol using sunlight efficiently (58). XRD study confirmed the percentage of phenol degradation for the given samples and the results showed that PtO and PtO_2 nanoparticles produced 67.5% and 32.5% of photodegradation respectively. The oxidation states of the metal play a vital role in photocatalytic degradation due to the presence of oxidation states such as Pt^0, Pt^{2+}, and Pt^{4+} (57) and the stability of the metal oxide depended on the number of oxygens present (18, 59). The order of photocatalytic activity and stability of PtO_2 are given below in (a) and (b) respectively.

(a) Photocatalytic reactivity order $Pt^0/PtO_2/TiO_2$ > TiO_2 > PtO_2/TiO_2
(b) Stability of PtO_2 order Pt_3O_4 > Pt_2O_3 > PtO_2 > PtO

The photocatalytic performance of PtO_2 has been investigated with Pt^0 formed during the CO oxidation reaction and positive potential of α-PtO_2. It has twenty times greater catalytic activity compared to Pt^0/TiO_2 in the presence of sunlight (60). Two different forms of PtO_2, α-PtO_2 and β-PtO_2, were prepared by various techniques but the physicochemical properties of α-PtO_2 are still not well understood (2). α-PtO_2 nanoparticles suspended in ethanol have been maintained for 20 days without interruption and the sample

was examined by gas chromatography to find the chromatographic peaks. α-PtO_2 nanoparticles showed outstanding durability for months at ambient temperature without a stabiliser (61). Pt/PtO_2 metal nanoparticles have exhibited activity for catalytic application in several reactions including reduction of organic substrates such as substituted phenol, pyridine derivative, methyl ethyl ketone, vanillin and salicylaldehyde (62). Recent research has presented easy ways to identify the photocatalytic efficiency of PtO_2 compared with TiO_2 and PtO_2/TiO_2 based materials (57, 63–65).

2.3 Catalysts in Electrochemistry

Pt/PtO_2 catalysts can be applied in the field of electrochemistry. PtO_2 has a high electron density compared to Pt metal, which can act as a nucleophile and react with electrophiles. Pt/PtO_2 has very strong stability in acidic medium during electrolysis at high potential, as studied by mass spectrometry (66). Pt/PtO_2 nanoparticles with particle size of 8 nm showed high catalytic activity compared to bulk Pt/PtO_2 due to their high surface area (67) and showed enhanced catalytic activity for the hydrogen evolution reaction (HER) with improved particle size control (66). Pt nanoparticles have been used as electrocatalysts in a wide range of applications such as chemical and petrochemical industries, automobiles and fuel cells (68). Pt nanoparticles were used for the manufacture of supported nanopore materials particularly in bipolar electrochemistry. It can be used for fluorescence in electrochemical microscopy. Bipolar electrochemistry is an important aspect of electrochemistry. A reaction is placed between two electrodes. One electrode works as an anode to oxidise the molecules and the other electrode acts as the cathode responsible for the reduction of molecules (69, 70). There are two types of bipolar cells in electrochemistry, open and closed bipolar cells (71). Such bipolar systems are prepared using nanomaterials such as nanoparticles, nanowires, nanorods and nanofilms (72). Pt nanoparticles were used to construct a nanoporous electrode by a focused ion-beam driven deposition technique and Pt nanoparticles were used in a coupled electrochemical cell prepared by focused ion-beam deposition. The supported Pt nanoparticles acted as the electrodes in electrochemical reaction with the help of a potentiostat which is shown in **Figure 2**.

Pt nanoparticles and nanoporous materials were reacted with gallium ions to fabricate nanoelectrodes with precise size and shape by a high focused beam technique and milling process. Conducting materials such as carbon, gold and tungsten were used to prepare electrodes for electrochemical reactions in which Pt acted as a highly efficient electrode due to its high stability, surface activity and electrocatalytic activity (73–75). Pt nanoparticles showed enhanced activity in the methanol oxidation reaction and have been used with supporting oxide materials in various fields such as catalytic supports (76),

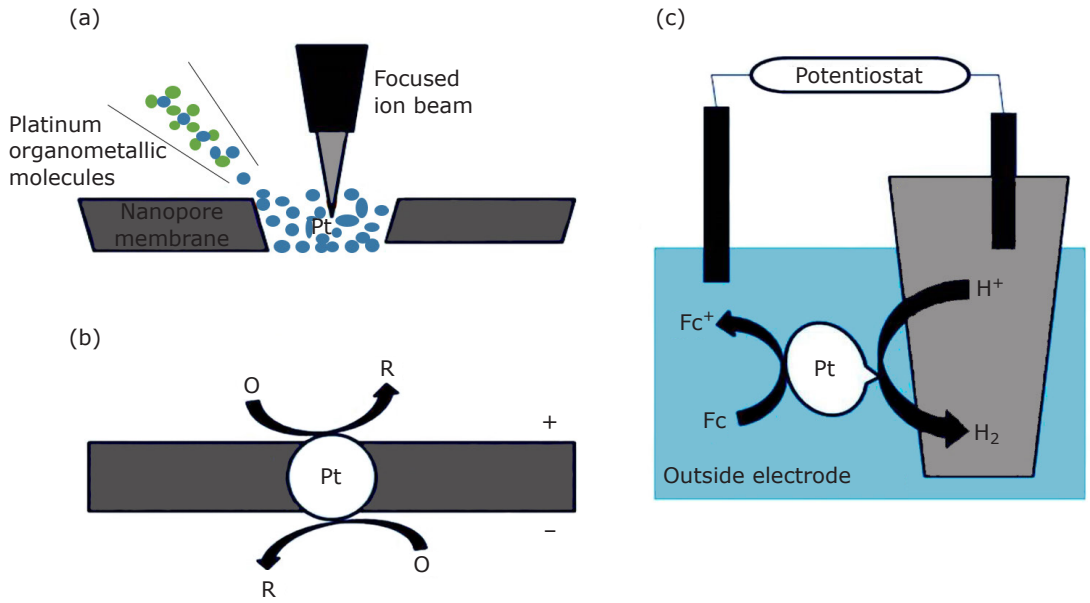


Fig. 2. (a) Construction of nanopore for focused ion-beam driven deposition technique; (b) coupled electrochemical focused ion-beam deposition; (c) supported Pt nanoparticles in electrochemical reaction

magnetic materials (77), photocatalysts (78, 79) and electronic systems (80).

Fe_2O_3 nanoparticles were found to perform well as catalysts due to their physicochemical properties. Fe_2O_3 supported by Pt (Fe_2O_3/Pt) materials have been used as an electrocatalyst for ORRs because of their high surface area, as shown in Equations (iv)–(vi) for the methanol electro-oxidation reaction (81, 82). **Figure 3** depicts the formation of Fe_2O_3 nanoparticles with supported Pt core-shell structure.

$$Pt + CH_3OH \rightarrow Pt\text{-}CO_{ads} + 4H^+ + 4e^- \quad (iv)$$

$$CH_3OH + H_2O \rightarrow CO_2 + 6H^+ + 6e^- \quad (v)$$

$$Pt\text{-}CO_{ads} + H_2O \rightarrow Pt + CO_2 + 2H^+ + 2e^- \quad (vi)$$

2.4 Biosensors

Pt nanoparticles are extensively used in biosensor applications, due to their wide range of magnetic properties (83, 84). Transition metals like Fe, Co and Ni, having magnetic characters, can be alloyed with Pt to form stable metal alloys such as Pt-Fe, Pt-Co and Pt-Ni with different physical and chemical properties such as magnetic anisotropy for use in biosensor applications (85). Biosensor materials should maintain a pH range of 5.0–9.0 in dispersed solution and simultaneously the temperature should be kept at 95°C (86). Sensors can be used for applications such as measurement of blood sugar levels for diabetic patients, removal of pollutants in water, food production and biotechnology (87, 88). Immobilised glucose oxidase has been used to predict the concentration of glucose with the help of electrochemical biosensors due to its superior suitability and excellent sensitivity (89). In recent years fibre optic sensors have been fabricated with the help of Pt nanoparticles using localised surface plasmon resonance (LSPR). This principle has mainly focused on chemical sensors and biosensors and is shown in **Figure 4**. LSPR sensing properties are based on size and shape. Therefore, sensitivity was increased with decreasing particle size and sensitivity was decreased with increasing particle size (for example 10 nm to 50 nm).

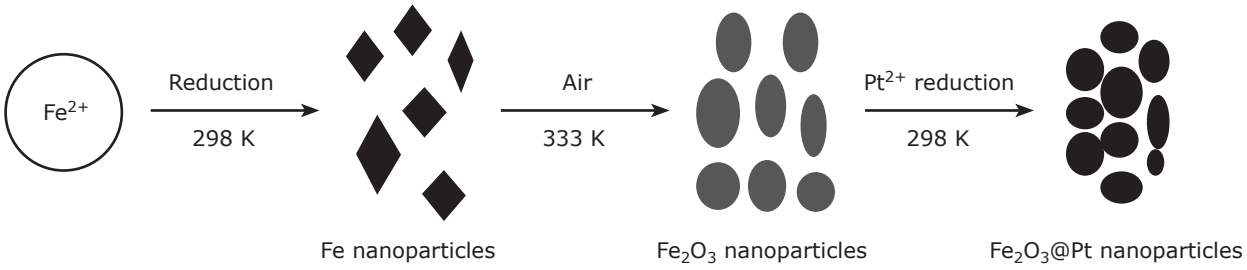


Fig. 3. Formation of Fe_2O_3 nanoparticles with supported Pt core-shell structure

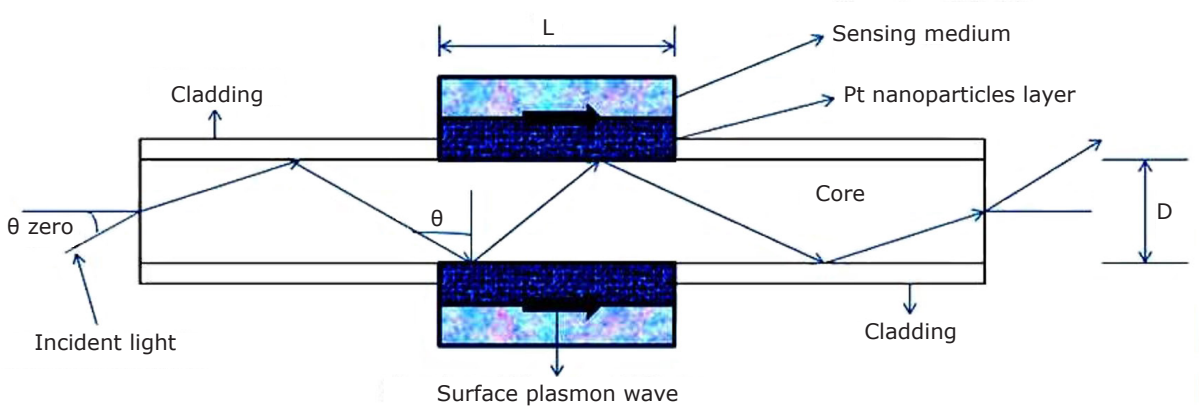


Fig. 4. Diagram for fibre optic sensor based on LSPR

Surface plasmon resonance (SPR) techniques have been used to investigate surface contact and sensing of liquids as well as other materials (90). Optical fibre was used for various purposes such as simplified and flexible optical design, remote sensing, continuous analysis or monitoring all based on SPR (91). Smaller size metal particles have comparatively high sensing and optical properties (92). Hence Pt metal is not only used in sensor applications but is also applicable in diverse fields such as optoelectronic devices, solar energy, jewellery (93), sensor materials, fuel cells, automotive applications, petroleum refining processes, hydrogen production and biomedical applications (94, 95).

Bisphenol A (BPA, 2,2-bis(4-hydroxyphenyl) propane), is used to manufacture polycarbonate and epoxy resin based plastics for food containers, water packets and plastic based medical containers. The nil effect concentration of BPA presented in drinking water and sea water values has been reported as 1.5 µg l^{-1} and 0.15 µg l^{-1} respectively (96, 97). BPA has been implicated in human health problems such as breast cancer, birth defects, infertility, diabetes and obesity (98, 99). Electrochemical sensors have been used to detect BPA through the oxidation reaction (100), by the presence of certain materials such as carbon (101), metal oxides and metals to activate electrodes (102–104). There is a need to find catalytic materials to increase the sensor activity by direct oxidation with no electrode side effects using materials such as carbon and metals such as Pt (105–107).

A new electrode system has been prepared with a porous dual-Pt leaf inside the outward top scanning electrode and inward bottom scanning electrode. A simple arrow indicates the dissemination transportation in the direction of the actively scanning electrode in **Figure 5**. A membrane between the Pt leaves is used to prevent short circuits during the redox process, as shown in **Figure 6** (108). Various factors play an important role for the enhancement of sensing capability, although surface area was found to be the main feature to increase sensor activity. For example, soft Pt provides low sensitivity and reduced selectivity for an enzymatic glucose sensor (109).

2.5 Functionalised Materials in Gas Sensor

Generally, sensors can detect nearby objects. Sensors are classified based on the nature of materials. The first type are physical sensors based on energy sources such as thermal, magnetic and mechanical energy. The second type are chemical sensors which can detect chemicals present in the body, atmosphere or environment. Gas sensors are an essential part of present day life due to the presence of various harmful or easily explosive gases such as isopropanol (IPA), methane, ethanol,

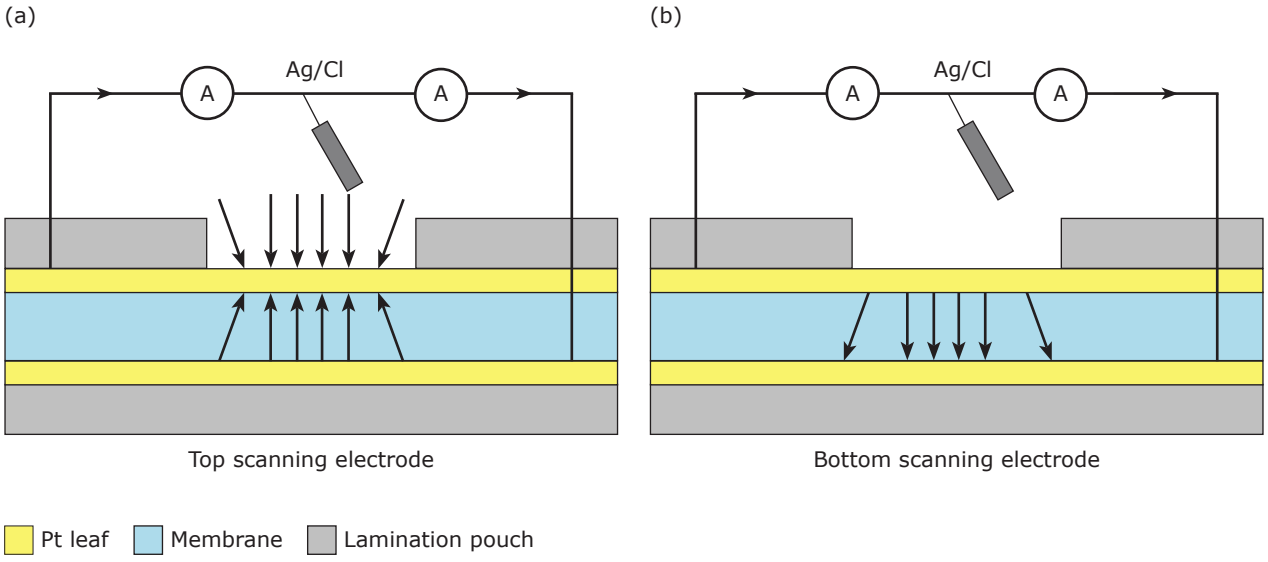


Fig. 5. (a) Dual-Pt leaves in outward top scanning electrode; (b) dual-Pt leaves in inward bottom scanning electrode. Reprinted from (108), with permission from Elsevier

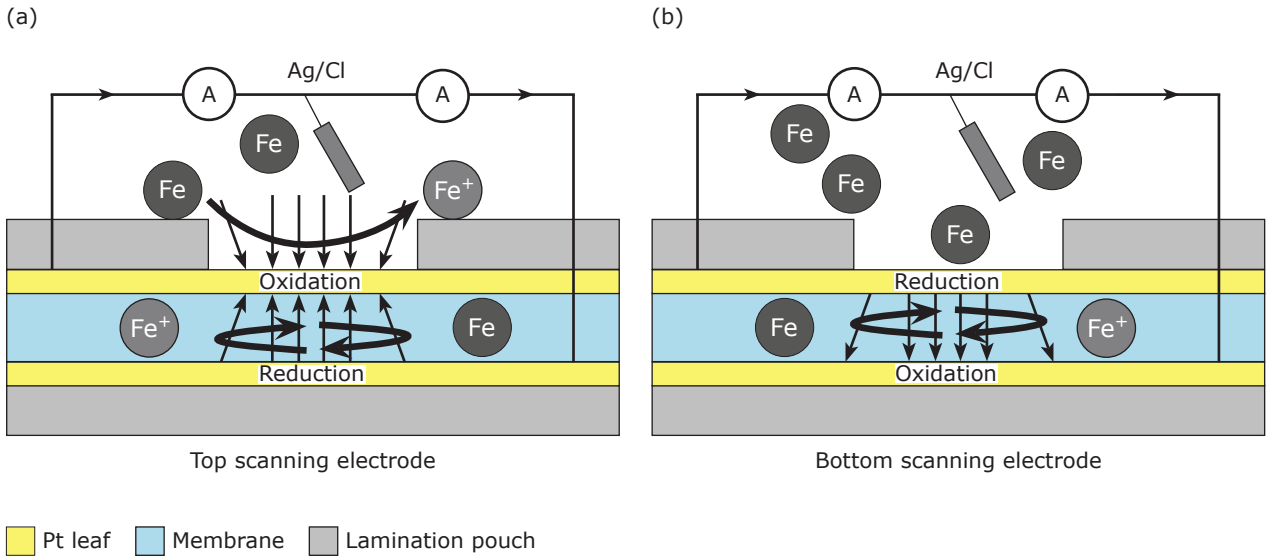


Fig. 6. (a) Diagram of top scanning electrode; (b) diagram of bottom scanning electrode. Reprinted from (108), with permission from Elsevier

methanol, formaldehyde, hydrogen, ammonia, hydrogen sulfide, nitrogen dioxide, sulfur dioxide and carbon monoxide, which cause health issues to human beings such as chronic bronchitis, emphysema and irritation, while high level concentrations can produce effects on the central nervous system, nausea and interior haemorrhage. Pt functionalised SnO_2 sheets have been used to detect IPA with a range of response values of 190.50 for 100 ppm of IPA at a controlled temperature of 220°C. It has excellent physicochemical properties and low cost, easy fabrication, high sensitivity and environmental safety (110).

In 2010 almost 665 gas leakages were recorded in Japan, including over 50 explosions. 60% of gas leakages were in residential areas. Therefore, gas sensors are essential to measure the gas and there are several materials already in use. These include platinum oxide (PtO_x) on graphene quantum dots on titania (GQDs/TiO_2) nanocomposite which behaves as a gas sensor to detect the highly aromatic volatile organic compound IPA with a sensor response range of more than 4.4 for a minimum concentration of 1 ppm and response within 9 seconds at room temperature. In addition, TiO_2 nanoparticles exhibit good surface area, unique optoelectronic properties, are easy to synthesise and have a narrow band gap. It can be coupled with graphene quantum dots as the composite materials acting as the gas sensors. Pt modified GQDs/SnO_2 thin film shows a transition from P-type to n-type sensing behaviour to sense acetone gas at room temperature with excellent results (111). Therefore, conjugated materials with the addition of metals and metal oxides such as Pt, Pd, Ni, PtO_2 and SnO_2 respectively can be used to enhance the gas sensing ability. A simple schematic diagram for a gas sensor which contains an alumina tube, sensor and test circuit are shown in **Figure 7** (112, 113).

3. Conclusions and Future Work

Nanomaterials play an important role in the fields of materials science, the medical industry, engineering and the polymer industry. This review article has covered selected applications of photocatalysts, electrochemical catalysts, biosensors and gas sensors. Further research work on nanosized Pt/PtO_2 will study areas like the stability of Pt materials, environmental aspects, biocompatibility, non-toxicity, suitability for various applications, electrochemical activity and chemical reactivity. There is currently interest in Pt/PtO_2 materials for emerging energy applications as it can produce excellent power conversion in various electrochemical applications such as fuel cells, batteries, capacitors, supercapacitors and solar materials, which were not covered in detail here. In fuel cells Pt plays a crucial role in electrochemistry as a counter electrode, due to no or minimum loss of energy conversion. Nanoscale Pt/PtO_2 is being used for removal of pollutants like sulfur and methane from industry and residential

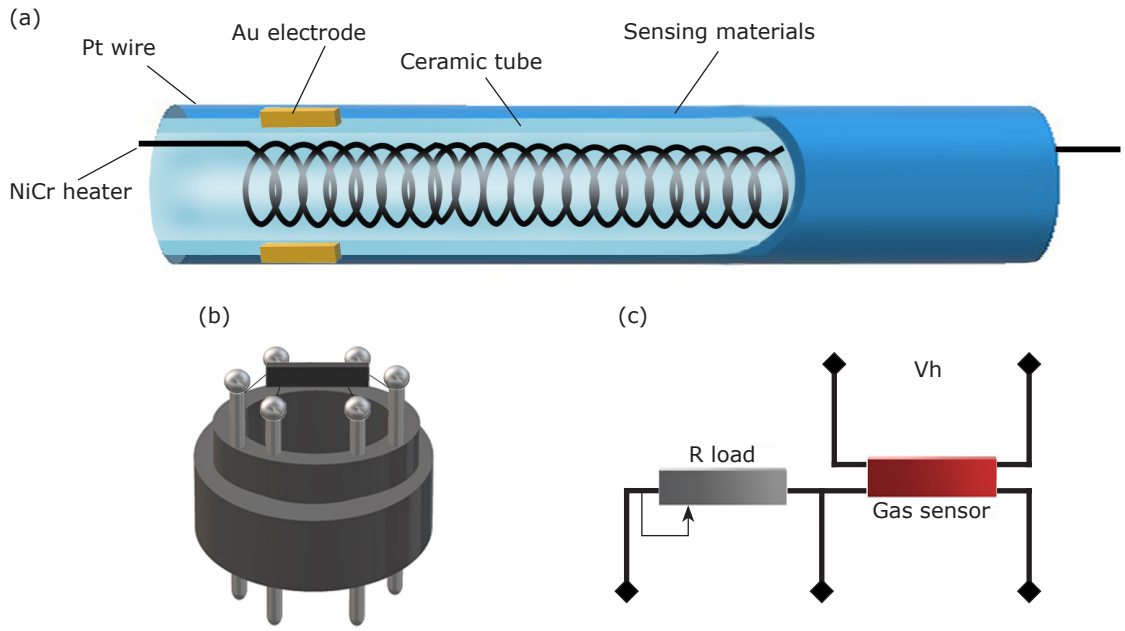


Fig. 7. Schematic diagrams of (a) alumina tube; (b) sensor; (c) test circuit. Reprinted from (112), with permission from Elsevier

areas and of CO_2 from the polymer industry and heavy-duty vehicles. In addition, it is used for the elimination of toxic and heavy metals such as lead, chromium and arsenic from the environment and from sewage or other waste waters, which can be purified by bio-sensing and electrochemical purification techniques for further usage including drinking if it meets water level recommendations and for agrochemical processes. Pt and PtO_2 based nanomaterials are also of great interest for future applications in spacecraft engines and low weight material applications due to their high ductility and thermal resistance properties. Pt and PtO_2 nanomaterials also behave as active catalysts in various chemical reactions, due to large surface area and porosity, particularly in the oxide form PtO_2 which is also under investigation for doping with other metals and alloys such as PtO_2-Pt, PtO_2-Fe and PtO_2-Co.

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