

We are IntechOpen, the world's leading publisher of Open Access books Built by scientists, for scientists

6,900

Open access books available

186,000

International authors and editors

200M

Downloads

Our authors are among the

154

Countries delivered to

TOP 1%

most cited scientists

12.2%

Contributors from top 500 universities



WEB OF SCIENCE™

Selection of our books indexed in the Book Citation Index
in Web of Science™ Core Collection (BKCI)

Interested in publishing with us?
Contact book.department@intechopen.com

Numbers displayed above are based on latest data collected.
For more information visit www.intechopen.com



Nanocomposite Films for Gas Sensing

Dongfang Yang

*Industrial Materials Institute, National Research Council Canada
Canada*

1. Introduction

Nanocomposite films are thin films formed by mixing two or more dissimilar materials having nano-dimensional phase(s) in order to control and develop new and improved structures and properties. The properties of nanocomposite films depend not only upon the individual components used but also on the morphology and the interfacial characteristics. Nanocomposite films that combine materials with synergetic or complementary behaviours possess unique physical, chemical, optical, mechanical, magnetic and electrical properties unavailable from that of the component materials and have attracted much attention for a wide range of device applications such as gas sensors. Recently, various nanocomposite films consisting of either metal-metal oxide, mixed metal oxides, polymers mixed with metals or metal oxides, or carbon nanotubes mixed with polymers, metals or metal oxides have been synthesized and investigated for their application as active materials for gas sensors. Design of the nanocomposite films for gas sensor applications needs the considerations of many factors, for example, the surface area, interfacial characteristics, electrical conductivity, nanocrystallite size, surface and interfacial energy, stress and strain, etc., all of which depend significantly on the material selection, deposition methods and deposition process parameters. This chapter will summarize recent developments in this new area of research including the fabrication methods currently in use for preparing nanocomposite films, transduction mechanisms for nanocomposite film gas sensors, types of the nanocomposite films suitable for gas sensors application, and the unique gas sensing properties of nanocomposite films.

2. Nanocomposite film fabrication methods

Materials can be deposited in the form of thin film (up to a few micrometer thick) on a substrate by a variety of methods such as physical vapour deposition, chemical vapour deposition, wet-chemical processes such as sol-gel and electrochemical deposition, thermolysis and flame spray pyrolysis etc.. Structural properties and composites of the nanocomposite films are strongly dependent on deposition techniques and deposition parameters. There are many more challenges to deposit composite films consisting of materials of very different nature such as a metal with a polymer or a metal oxide with a metal, than to deposit films of only one type of material. Any deposition process that can be used to prepare nanocomposite films should be able to simultaneously vaporize or coat materials of different nature onto the same substrate to form the composite films. To deposit

composite materials of different natures by precisely controlling their chemical composition, surface morphology, microstructure, and phase remains a challenge. This section will summarize the most common deposition methods used for the fabrication of nanocomposite films for gas sensor applications.

2.1 Physical vapor deposition

Physical vapour deposition (PVD) is referred to a variety of vacuum deposition methods that are used to deposit thin films by the condensation of the vaporized form of materials onto various substrate surfaces. The coating method involves only purely physical processes such as high temperature vacuum evaporation using electron beam or resistance heating, plasma sputter bombardment and pulsed laser deposition. To deposit nanocomposite films by PVD processes, the energy sources, such as electron beam, laser, and plasma, must be able to vaporize component materials under the same processing parameters such as power, energy, temperature and vacuum level, and then condense them at the same time onto a substrate surface to form the composite film.

Sputter deposition is one of the PVD processes that uses a sputtering gas such as argon to sputter composite material sources (a target consisting of pre-mixed compounds or a few targets simultaneously sputtering by ions) which then deposits them onto a substrate to form thin films. Nanocomposite films consisting of mixed metal oxides, a metal and a metal oxide, or a metal and a polymer can be deposited by the sputtering method. Pulsed laser deposition (PLD) is another PVD process that can be used to deposit nanocomposite films. The PLD uses a high power focused pulsed laser beam to ablate targets of materials to be deposited to form a deposited thin film on the substrate inside a vacuum chamber. Since laser beams are much easier to transport and manipulate, and does not interact with gas-phase species, the dynamic range of deposition pressures is the largest compared to other vacuum deposition processes. Typical laser wavelengths used in PLD process are less than 250 nm. In such short wavelength, virtually any material can be laser evaporated leading to the possibility for depositing composite films consisting of a variety of materials. Nanocomposite thin film material can be easily deposited by PLD using a target consisting of pre-mixed powder of source materials or ablating multiple targets of different materials simultaneously. The ability of the technique to reproduce the target composition is a unique feature for controlling the composition of nanocomposite films. Fig. 1 shows a typical PLD apparatus used for deposition of Au-WO₃ nanocomposite films. The KrF laser beam, operating at 248 nm wavelength, was used to subsequently ablate a rotating WO₃/Au composite target, which was formed by mounting a pie-shaped piece of Au target over a circular WO₃ target as shown in Fig. 1. The vapours from both Au and WO₃ are condensed and mixed on a substrate to form the Au-WO₃ nanocomposite film. To improve the film homogeneities, the substrates were rotated along the vertical axis at a speed of 35 rpm (Yang, 2008). High temperature vacuum evaporation is also a PVD process suitable for depositing nanocomposite films. This technique consists of pumping a vacuum chamber to low pressures and heating the material to produce a flux of vapour and condensing it onto a surface. The material to be vaporized is typically heated by using an electrically resistive heater or electron beam until its vapour pressure is high enough to produce a flux. For depositing nanocomposite films, powders of two or more materials were mixed and compressed into pellets for evaporation. It is also possible to vaporize multiple pellets of different materials using multiple heating sources. The flux of each material can be controlled individually by increasing or decreasing the power of

the heating source or exposed area of the materials in the vacuum. Vacuum evaporation is very useful for nanocomposite thin film fabrication due to ease of uniform mixing over a wide range of concentrations.

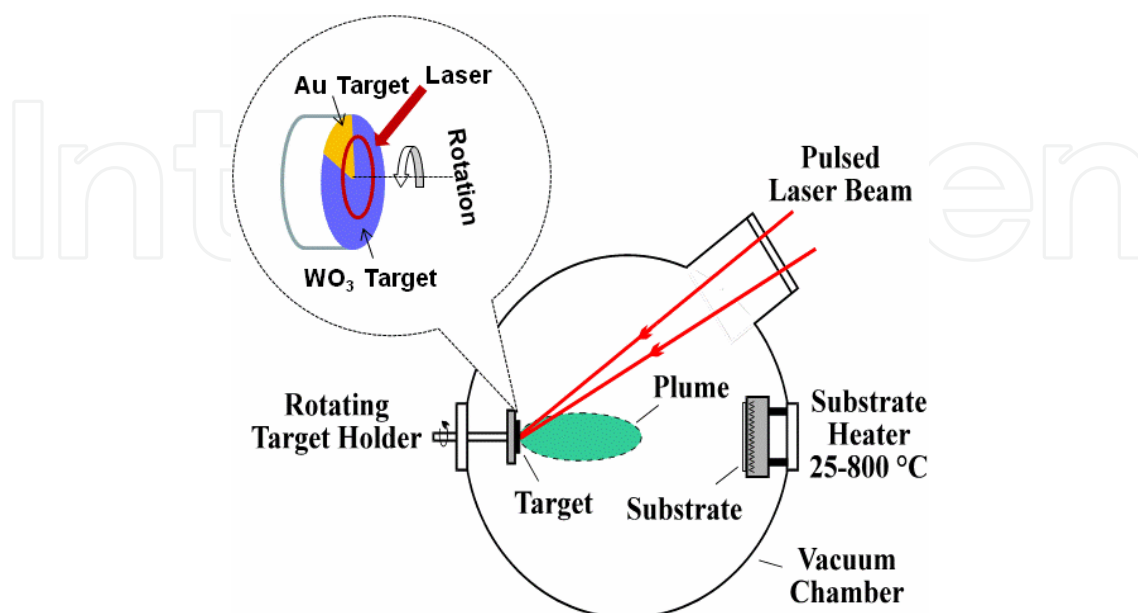


Fig. 1. A typical PLD apparatus used to deposit nanocomposite films. The laser beam subsequently ablates rotating WO_3/Au composite targets to produce the Au-WO_3 nanocomposite films

2.2 Sol-gel and other wet chemical synthesis

The sol-gel process is a wet-chemical technique that is widely used to deposit nanocomposite films. In this process, sol (or solution) containing sources for component materials, such as metal alkoxides and metal chlorides precursors for metal oxides, metallic nanoparticles for metals, tetraethoxysilane for silica matrix, catalysers, stabilizers and other additives for porosity generation, was prepared first. The sol then undergoes hydrolysis and polycondensation reactions to evolve gradually towards the formation of a gel-like network containing both a liquid phase and a solid phase. The basic structure or morphology of the solid phase can range anywhere from discrete colloidal particles to continuous chain-like polymer networks. The formation of the nanocomposite film from the sol-gel precursor involves either dip coating or spin coating on a substrate, decomposition and pyrolysis of organic compounds, removal of water and residual organics from the resulting network followed by nucleation and growth of the crystallites. The thermal decomposition behaviour of the gel precursor plays an important role in crystallites size and in film porosity. Sol-gel is an excellent technique for preparing high purity multicomponent films. Various types of nanocomposite films have been prepared by the sol-gel process and used as active materials for gas sensors.

Beside sol-gel process, other wet chemical processes were also used to synthesize nanocomposite films. For example, successive ionic layer deposition (SILD) method was used to prepare $\text{SnO}_2\text{-Au}$ nanocomposites using HAuCl_4 and SnCl_2 as the precursors (Korotcenkov, 2009). The SILD method consists essentially of repeatedly successive treatments of the substrate surface with solutions of various salts such as acetates, chlorides,

and nitrates of various metals. Electrophoretic deposition process is another wet-chemical process used to incorporate metal nanocrystals into the mesoporous metal oxide films to form metal-oxide nanocomposites films. In the process, the mesoporous metal oxide films are immersed in metallic nanocrystal dispersion. Under applied electrical potential, metallic nanocrystals are infused into the inside of mesoporous oxide film to form the nanocomposite films.

2.3 Chemical vapor deposition and flame spray pyrolysis

Chemical vapour deposition (CVD) is a chemical process that can be used to produce thin nanocomposite films. In a typical CVD process, the substrate is exposed to more than one volatile precursor, which reacts and/or decomposes on the substrate surface to produce the desired composite films. However, only few papers reported using the CVD process to produce nanocomposite films for gas sensor applications. Flame spray pyrolysis is a one step combustion process of solution precursors to produce nanocomposite materials of mixed oxides. Particle size can be produced in the range of 10 nm to 100 nm depending on process parameters. A binder and solvent were then used to mix the nanocomposite particles prepared by pyrolysis to form a paste prior to doctor-blade coating on the substrates to form thin films or thick films for gas sensor applications.

3. Transduction mechanisms for nanocomposite film gas sensors

A gas sensor is an electronic device that consists of a transducer and a sensitive element (an active layer such as a nanocomposite film) that relies, for its operating mechanism, on one of its physical and chemical properties. Basically it operates as follows: a charge transfer occurs between gas molecules and the “sensitive” nanocomposite films, resulting in an electrical and/or optical signal that is related to the gas molecules type and number. Due to its nanoscale morphology and aggregation, the surface-to-volume ratio and quantum confinement, nanocomposite “sensitive” films with high sensitivities, improved selectivity and reduced operating temperatures have been demonstrated. The following section summarizes various types of transducers that utilize different operating mechanisms for the nanocomposite film gas sensors.

3.1 Chemoresistive sensors

Chemoresistive response of nanocomposite films is based on the modification of electrical conductivity of the nanocomposite films due to adsorbed gas species. Chemoresistive effects are perhaps the most attractive measurable responses since very precise readings may be achieved with minimal electronics. To fabricate a chemoresistive gas sensor, nanocomposite films are deposited on to a substrate provided with interdigital electrodes made from either Pt or Au. A thin film heater made from Pt or NiCr is always fabricated on the backside of the substrate as a heater to provide high operating temperature requirement. The resistance of the nanocomposite film is monitored when the film is exposed to different gases. A typical apparatus for testing chemoresistive gas sensor is shown in Fig. 2. The sensor under test was loaded in a glass chamber and the electrical resistance of the sensor was measured by a multi-meter through two conductive needles when a target gas was injected into the chamber. Chemoresistive response is the most common transduction mechanisms for gas sensors based on nanocomposite films.

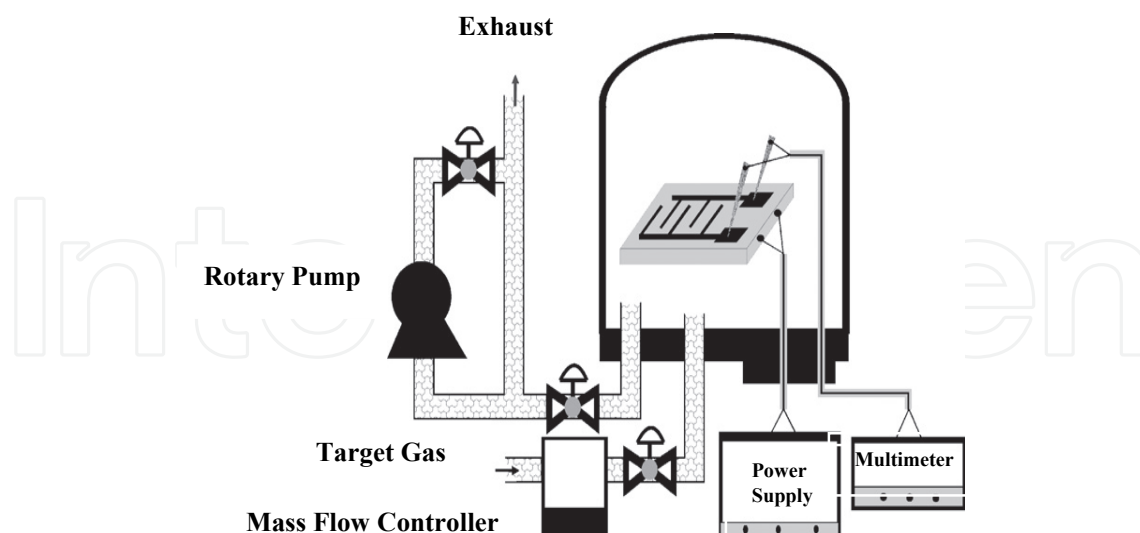


Fig. 2. Apparatus for testing chemoresistive gas sensor

3.2 Optical sensors

Optical gas sensors are based on the modification of optical responses of a nanocomposite film induced by interaction with gas molecules. This approach presents a number of advantages over the chemoresistive sensor. Electromagnetic waves are described by a certain number of degrees of freedom such as intensity, wavelength, and polarization: optical sensing thus allows multi-parametric detection, which is not possible in electrical sensing where only a single scalar quantity (electrical conductivity) is involved. Optical sensors do not need electrical contacts, do not suffer from electromagnetic noise and may allow optoelectronic integration and have the potential of multi-gas detection. Different optical responses may be involved in optochemical gas sensing, such as reflectance, absorption, surface plasma resonance or photoluminescence. Examples of optical sensors include white light interferometry of polymer nanocomposite films to measure their swelling sensitivity when exposing to gas vapours (Mauro, 2009), optical absorption of Au-TiO₂ nanocomposite films for the detection of CO and H₂ (Buso, 2008), and surface plasmon resonances of the metal nanoparticles in metal-metal oxide nanocomposites (Yang, 2008 & Fernández, 2005 & Manera, 2008). Recently, nanocomposite films with gas sensing functionality have become a new area of interest for optical gas-sensing applications.

3.3 Surface acoustic wave sensors

The operational principle of an acoustic wave gas sensor is a travelling wave combined with a confinement structure to produce a standing wave whose frequency is determined jointly by the velocity of the travelling wave and the dimensions of the confinement structure. Surface acoustic wave gas sensors obtain their gas sensitivity from a chemically active nanocomposite film coated on top of the acoustic device, which interacts with the surrounding gases. The acoustic wave travelling in the coated device particularly penetrates into the adjacent composite film, translates and deforms the film, thereby probing its mechanical properties, its thickness and the acoustic properties at the upper film surface.

The chemical interaction on the surface of a nanocomposite film leads to a change in acoustic wave propagation, which in turn yields a change of the electrical response of the sensor. The quartz crystal resonator is the most common device used as an acoustic-wave-based sensor. The simple geometry of the device and the predominant thickness-shear mode of the propagating wave are propitious conditions for a comprehensive derivation of the acoustic-electrical behaviour of quartz crystal devices. Examples of surface acoustic wave gas sensors using nanocomposite films include TiO₂-porphyrin nanocomposite thin film coated on a quartz crystal was used to detect volatile organic compounds such as ethanol, acetone, 2-propanol, cyclohexane, toluene and o-xylene (Arshad, 2008) and a polyaniline-indium oxide nanocomposite thin films gas sensor was fabricated on AT-Cut quartz crystal microbalance (QCM) of Ag electrodes for analyze CH₄ and CO gases (Yan, 2009).

4. Types of nanocomposite films

Nanocomposite films consists of nanocrystalline or amorphous phase of a least two different materials. Depending on the nature of the component materials, micro/nanostructure and surface/interfacial characteristics, various unique gas sensing properties can be realized by using nanocomposite films as the active layer. Improvement in gas sensitivity, selectivity, stability, as well as reduction in the response time and operating temperature has been demonstrated by various types of nanocomposite films. In the following section, the fabrication and unique gas sensing properties of various types of nanocomposite films such as metal-metal oxide, mixed metal oxides, polymers mixed with metals or metal oxides, or carbon nanotubes mixed with polymers, metals or metal oxides will be described.

4.1 Metal-metal oxide nanocomposite films

Nanocomposite films that consist of metal nanoparticles dispersed in a matrix of metal oxides have recently attracted much interest as materials for gas sensors. Metal-metal oxide nanocomposites have physical properties that differ from those of the nanostructured single phase metal oxides. The metal nanoparticles play both passive and active roles in the sensing process. The presence of metal nanoparticles increases the active surface area and improves gas diffusion inside the film. Metal nanoparticle also reduces the electrical resistance and increases the optical absorption of metal oxide. Metal nanoparticles such as platinum (Pt), palladium (Pd), gold (Au), palladium (Pd) and silver (Ag) also show catalytic properties that can modify the analyte-metal oxide chemical interactions and enhance the sensing process. The interfacial region between metal nanoparticle and metal oxide also has very different electron band structure than inside the bulk semiconducting metal oxide, which also contribute to the unique gas sensing properties of this type of nanocomposite.

Fabrication

The amount and distribution of the metallic nanoparticles in a metal oxide matrix is an important parameter to be controlled in order to obtain highest gas sensing sensitivity. Diverse methodologies including PVD, impregnation, sol-gel, and electroless plating have been used to introduce metal nanoparticles into the metal oxide matrix. For example, reactive magnetron sputtering was used to deposit Pd-doped SnO₂ nanocomposite films with tetragonal SnO₂ structure and columnar nanograins at the substrate temperature of 300 °C and discharge gas pressure of 1.5, 12, and 24 Pa. The discharge current was fixed at 80

mA, and the discharge voltage showed a value between 280 and 260 V, depending on the discharge gas pressure. It was found that a porous film could be formed at a high discharge gas pressure and a low substrate temperature (Shen, 2009). Metal-metal oxide nanocomposite films can also be deposited by the PLD. For example, gold-zinc oxide nanocomposite films have been synthesized by subsequent laser ablation of zinc and gold targets using either an UV KrF excimer or a frequency tripled Nd:YAG laser. The optical properties of the gold-zinc oxide nanocomposite films can be tailored by proper choice of the relative number of laser pulses used for the ablation of the gold or zinc targets (Gyorgy, 2008). Surface plasma resonance (SPR) gas sensors using very thin Au-WO_{3-x} nanocomposite thin films were also fabricated by PLD and the content of Au in the composite films was also varied by altering the relative laser ablation time on Au and WO₃ targets, respectively (Yang, 2008).

Dot- and rod-shaped Au-TiO₂ nanocomposite films were prepared by a sol-gel method for SPR sensing of alcohol vapours. For the synthesis of Au-TiO₂ nanocomposite films, firstly, a sol using titanium isopropoxide, isopropanol and acetic acid with a molar ratio of 1:6:1.3 was prepared. Then, a colloidal solution containing Au spherical nanoparticles was prepared and mixed with the sol. Colloidal gold was synthesized by reducing HAuCl₄ with tris-sodium citrate in water and then dispersed in ethanol by using poly(nvinylpyrrolidone) as a stabilizer. The mixed sol was spin coated onto fused silica slides following by drying and heat treatment to form the thin films (Manera, 2008). Other metal-metal oxide nanocomposite films prepared by sol-gel processes include the SnO₂-Ag nanocomposite (Gong, 2006); Au-TiO₂-NiO nanocomposites (Gaspera, 2010) and Au-TiO₂ nanocomposite films for sensing vapour organic compounds by Surface Plasmon Resonance and optical absorption (Fernandez, 2005). Beside sol-gel process, other wet chemical processes were also used to synthesize metal-metal oxide nanocomposite films. SnO₂-Au nanocomposites were deposited by the SILD method on a substrate coated with un-doped SnO₂ films of thickness ~50–55 nm using HAuCl₄ and SnCl₂ as the precursors. The thickness of the SnO₂-Au nanolayer on the surface of the SnO₂ films was controlled through the number of deposition cycles (Korotcenkov, 2009). A significant limitation in SILD deposition relates to the repeated treatment of the growing film, which is necessary for the synthesis of the multilayer, but it can cause re-dissolution of the film in the solution during repeated treatment. Electrophoretic deposition process can also be used to deposit metal-metal oxide nanocomposite films. For example, the mesoporous TiO₂ on ITO/glass was immersed in Au nanocrystal dispersion in chloroform. A potential of 25 or 50 V was applied to infuse the Au nanocrystals inside the mesoporous TiO₂ film to form the Au-TiO₂ nanocomposite films. The ligands such as dodecanethiol on the Au nanocrystals prevented aggregation. The films were highly conductive, and are suitable for sensor applications (Patel, 2007 & Mehul, 2008).

Unique properties

Metal-metal oxide nanocomposite films combine the catalytic property of metal and gas reactivity of semiconducting metal oxide, thereby possess unique gas sensing properties unavailable from either the metal or metal oxide alone. Metallic nanoparticles activate or dissociate the detected gas on their surface. These activated products are easier to react with the adsorbed oxygen species on the metal oxide surface, resulting in a change of resistance. In addition, direct exchange of electrons between the semiconductor metal oxide and metallic nanoparticles causes a change in the width of the depletion layer of the semiconductor oxide, leading to a change in sensing properties. The embedded metal

nanoparticles can reduce the sensing temperatures, improve the selectivity, and increase the surface area of the metal oxide.

Sun et al. (Sun, 2009) investigated the Pd-doped SnO_2 nanocomposite films for H_2 gas sensing. They found that the composite films show reversible response to H_2 gas and their sensitivity is better than undoped SnO_2 films. Fig. 3a shows the sensitivity of undoped and Pd-doped SnO_x thin films measured at 100, 125 and 150 °C when exposed to 250 ppm H_2 . The Pd-doped SnO_x has a sensitivity about one or two orders of magnitude higher than the undoped SnO_x at each temperature investigated. Fig. 3b shows the response transients of two films at 150 °C. For undoped and Pd-doped SnO_x thin films, the response time was 14 and 10 min, respectively. Clearly Pd-doped SnO_x reduces the response time.

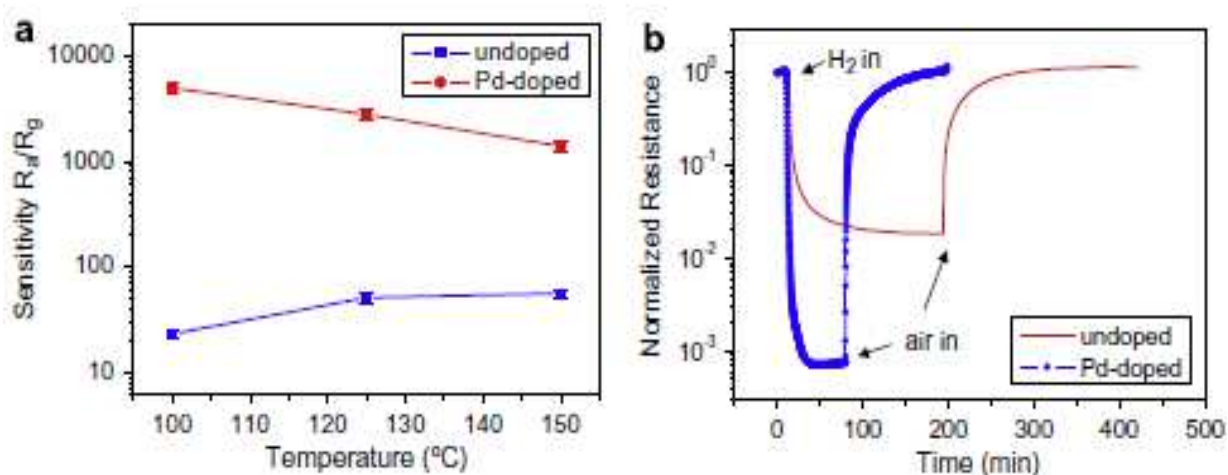


Fig. 3. (a) H_2 gas sensitivity of undoped and Pd-doped SnO_x thin films measured at different temperatures. (b) Response transients of both films obtained at 150 °C. The concentration of H_2 is 250 ppm diluted in N_2 (Sun, 2009).

The influence of Pd doping on the microstructure of SnO_x thin films was investigated by SEM and TEM. Fig. 4a and b shows the SEM secondary electron images of undoped and Pd-doped films, respectively, while the corresponding TEM images are shown in Fig. 4c and d. It is clear that the undoped film has larger pores and grain size than the Pd-doped film. The histograms of the grain size distributions measured by TEM are plotted in the insets of Fig. 4c and d. The grain size distributions of both films are fitted with a log-normal distribution. The average grain size of the undoped and Pd-doped SnO_x films is 15 and 9 nm, respectively. Knudsen gas diffusion and depletion layer models were employed by Sun et al. to evaluate the microstructure influence on the gas sensitivity. Their results suggest that the microstructure of the Pd-doped film is critical for improving the gas sensitivity, but cannot account for the total sensitivity enhancement. They believed that other mechanisms could also play important role and the electronic and chemical activities of Pd could be the primary factors for the sensing enhancement (Sun, 2009).

Au- TiO_2 nanocomposite films were used by Buso et al. (Buso, 2008) as both optical and chemoresistive sensors for the detection of CO and H_2 . Tests performed at 360 °C show CO- and H_2 -induced reversible variations in the optical absorption of thin Au- TiO_2 nanocomposite films. The absorbance changes are strongly dependent on both the testing wavelength and the film microstructure. The reactant gases CO and H_2 were suggested to initially adsorb into the titania matrix. Once oxidized the liberated electrons then flow to

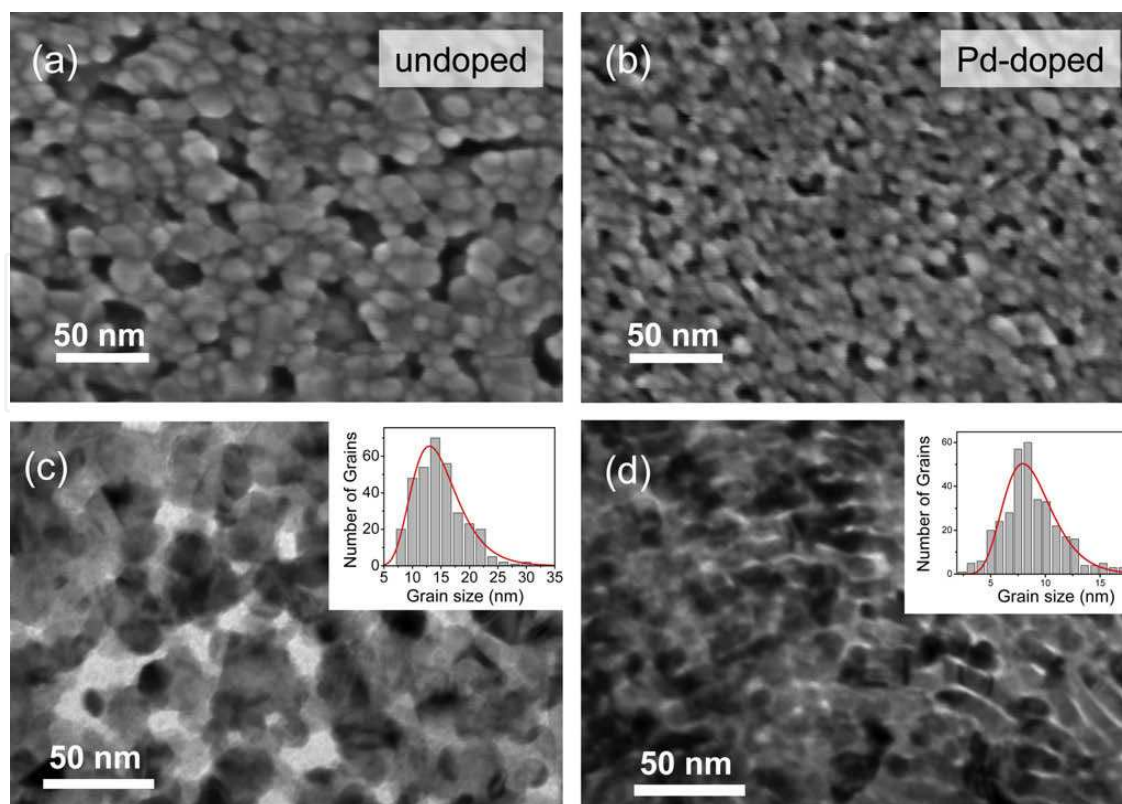


Fig. 4. (a) and (b) SEM secondary-electron images and (c and d) TEM bright-field images of undoped and Pd-doped SnO_x films annealed at 700°C for 1 h. Grain size statistics from TEM images are shown in the insets of (c) and (d). The distribution was fitted using log-normal probability density function (Sun, 2009).

and are trapped on the gold nanocrystals. Gas adsorption in the matrix sites near the Au nanoparticles could lead to local changes in refractive index of TiO_2 , which, in principle, are capable of affecting the absorption spectral changes. Mehta et al. (Mehta, 2005) investigated In_2O_3 -Ag nanocomposite films having well-defined individual nanoparticle size and composition for ethanol gas sensing application. For a pure In_2O_3 nanoparticle film with particle size of 11 nm, they observed the sensitivity of 325 and the response time of 8 s at 400°C for 1000 ppm ethanol, while for In_2O_3 -Ag nanocomposite film, the sensitivity increases to 436 and the response time is reduced to 6 s. They believed that Ag additives form a p-type Ag_2O , which interact with n-type In_2O_3 to produce an electron-deficient spacecharge layer. In the presence of ethanol, interfacial Ag_2O was reduced to Ag, creating an accumulation layer in In_2O_3 resulting in increased sensitivity (Mehta, 2005). Gong et al. (Gong, 2005) discovered that SnO_2 -Ag nanocomposite films have very high sensitive to hydrogen sulfide: as low as 1 ppm concentrations of H_2S at low working temperature of 70°C can be detected by the composite films. The SnO_2 -Ag films are also less sensitive to common interference gases such as Cl_2 , HCl , SO_2 , C_6H_{14} , CH_4 , CO , C_3H_8 . Korotcenkov et al. deposited a SnO_2 -Au nanocomposites film over a pure SnO_2 surface and studied its response to reducing gases such as CO and H_2 (Korotcenkov, 2009). They found that by increasing the thickness of the SnO_2 -Au nanocomposite layer, the sensor response and the recovery times were decreased. The ZnO films with embedded noble-metal nanoparticles (Pt, Au and Ag nanoparticles) also exhibit enhanced sensitivity and fast initial recovery behavior compared to those without metal nanoparticles (Mishra, 2005).

Due to the localized surface plasmon resonance (SPR) of the metal nanoparticles, metal-metal oxide nanocomposite films can also be explored as plasmonic-based optical gas sensor using their unique optical properties. SPR responses of Au-WO_{3-x} and Ag-WO_{3-x} nanocomposite films with either stoichiometric ($x = 0$) and non-stoichiometric ($x > 0$) structures were simulated using effective medium theory and Macleod's general characteristic matrices method for various metal percentages and film thicknesses in the Kretschmann configuration at the wavelength of 632.8 nm. The simulation results predicted that the Au-WO_{3-x} and Ag-WO_{3-x} nanocomposite thin films with 40-80% metal fractions and film thickness of 30-50 nm are applicable for optical gas sensing (Deng, 2008). We also observed that SPR response of Au-WO_{3-x} nanocomposite films changed when exposed to low ppm of NO gas which indicated that gas sensing using the SPR responses of metal-metal oxide nanocomposite films is feasible (Yang, 2008). Thin films composed of Au nanoparticles dispersed inside a TiO₂-NiO mixed oxide matrix were also investigated by Gaspera et al. (Gaspera, 2010) as hydrogen sulfide optical sensors using the Au-localized SPR. The detection sensitivity is shown to be down to a few ppm of H₂S, and almost no interference in response is observed during simultaneous exposure to CO or H₂. The high sensitivity and selectivity of the Au-TiO₂-NiO nanocomposite film for H₂S detection is believed to be due to direct catalytic oxidation of H₂S over the Au-TiO₂-NiO nanocomposite film (Gaspera, 2010). Manera et al. (Manera, 2008) discovered that dot- and rod-shaped gold nanoparticles embedded TiO₂ thin films possess optical absorption sensing responses towards different kinds of alcohol vapours in the spectral range corresponding to the SPR peak of the gold nanoparticles. Total attenuation SPR measurements in controlled atmosphere by them revealed that the sensing property is due to variation of the thickness and the real part of the active sensing layer refractive index. Au-TiO₂ film is another metal-metal oxide nanocomposite film that was investigated for optical gas sensing of different vapour organic compounds (Fernández, 2005). All the above results clearly indicate that metal-metal oxide nanocomposite films offer a real opportunity for optical gas sensing with rapid and sensitive response to many common gases.

4.2 Mixed metal oxides

Transition metal oxides have promising gas sensing performance due to their catalytic properties. Some transition metal oxides are stable, have low electric resistance and good gas sensing properties at low operating temperature, while others have high electric resistivity and require high operating temperatures. Some of the oxides are more sensitive to oxidizing gases while others are more to reducing gases. It is therefore a natural approach to combine metal oxides of different properties with an appropriate proportion so that gas sensor performance can be modified as desired.

Fabrication

Although PVD, sol-gel and pyrolysis can be used to deposit mixed metal oxide nanocomposite films, sol-gel method is the most cost-efficient method as it represents a simple processing alternative to the vacuum deposition techniques. Various mixed metal oxide nanocomposite films have been prepared by the sol-gel process. For example, cobalt oxide-SiO₂ nanocomposite films were deposited on glass substrate by Musat et al. (Musat, 2008) using [Co(CH₃COO)₂].4H₂O, tetraethoxysilane and CH₃(CH₂)₁₅N(CH₃)₃Br surfactant as starting materials. After each layer was deposited on a substrate by dipping, the gel film was dried at 70 °C and then pre-heated in air at 400 °C. The procedure was repeated 2 or 3

times. The stabilized films were then post-heat treated in air at 500 °C for cobalt oxide crystallization. The effect of withdrawal speed, number of layers and thermal treatment on the crystalline structure, morphology, Co-doping states, optical, electrical and gas sensing properties of the thin films were investigated. When using sol-gel process for the deposition of ZnO-SiO₂ nanocomposite films, zinc acetate (Zn(CH₃COO)₂·2H₂O) was used as the ZnO nanoparticles source, tetraethoxysilane (TEOS) as a silica matrix source and cetyl trimethylammonium bromide (CTAB) as a surfactant for porosity generation. The chemical nature of ZnO source (zinc acetate solid salt, zinc acetate alcoholic solution or ZnO nanopowder) used for the sol preparation was found to significantly affect the thermal decomposition of complex precursor and the microstructure and properties of the nanocomposite thin films (Musat, 2008). Thin SiO₂-NiO and SiO₂-Co₃O₄ nanocomposite films consisting of either NiO or Co₃O₄ nanocrystals in a porous SiO₂ matrix were also prepared by the sol-gel method, in which one solution containing the silica (mixture of tetraethoxysilane, methyltriethoxysilane, H₂O, HCl and EtOH) was mixed with another solution containing the metal oxide precursor (dissolving CoCl₂·6H₂O or NiCl₂·6H₂O in EtOH). Either 3-aminopropyl triethoxysilane or N-[3-(trimethoxysilyl)propyl]-ethylenediamine molecules was added to the solution to coordinate the Co²⁺ or Ni²⁺ cations (Cantalini, 2005). Other mixed metal oxides nanocomposite films prepared by the sol-gel process include SiO₂-NiO films ((100-X)SiO₂-XNiO with X = 10, 20, 40) (Martucci, 2003); MoO₃-TiO₂ films (Li, 2001); Fe₂O₃-SnO₂ films for detecting NO₂ and C₂H₅OH gas (Kotsikau, 2004); NiO-SiO₂ films for detection of H₂, CO and humidity (Martucci, 2004 & Martucci, 2003); In₂O₃-SnO₂ film for detecting H₂ at ppm-level at room temperature (Satyajit, 2005); and Li and Ti co-doped NiO nanocomposites (Li_{0.1}Ti_{0.018}Ni_{0.882}) for detecting toluene, ethanol and chloroform (Qureshi, 2009).

PVD process has also been used to deposit mixed metal oxide nanocomposite films. Wisitsoraat et al. (Wisitsoraat, 2007) used oxygen ion-assisted electron beam evaporation to prepare various TiO₂ based mixed oxide nanocomposite films such as TiO₂-WO₃, TiO₂-MoO₃, TiO₂-NiO_x, and TiO₂-ZnO. They first mixed TiO₂ powder with WO₃, MoO₃, NiO_x, or ZnO powders, and then pressed the mixed powder to form pellets. Electron beam evaporation of the pellets occurs in vacuum chamber to form mixed oxide films. After annealing the films in air at 500 °C, various TiO₂ composite films having nanocrystalline structure with fine grain size ranging from 10-50 nm were prepared. Flame spray pyrolysis was also used to prepare WO₃-doped ZnO nanoparticles (Siriwong, 2009).

Unique properties

Mixing metal oxides of complementary behaviours forms a new class of nanocomposite materials. This type of nanocomposite films show a significant improvement in gas sensing properties. For example, by embedding transition metal oxide nanoparticles such as NiO and Co₃O₄ in a porous silica glass matrix, the nanoporosity of such composite matrix provides a path for the gas molecules to reach the functional ultrafine NiO and Co₃O₄ particles. The sensor response of the NiO-SiO₂ and Co₃O₄-SiO₂ nanocomposite films to H₂ (20-850 ppm) and CO (10-500 ppm) in dry air and at different operating temperatures (50-300°C) has been investigated by Cantalini et.al using both conductometric and optical transmittance transduction methods (Cantalini, 2005). Both the NiO and Co₃O₄ doped films exhibit a conductometric p-type response, with a resistance increase upon exposure to the reducing gas. The nanocomposite films also showed a reversible change in the optical transmittance in the vis-NIR range when exposed to CO (10-10,000 ppm) in dry air. SiO₂-

NiO films have shown the highest response to H_2 at 300°C operating temperature and good selectivity to H_2 when CO is the interfering gas. Selectivity tests shown in Fig. 5 comprise a first exposure (first section) to 200 ppm H_2 target gas in dry air, followed by a second exposure (second section) where the films are subjected to 200 ppm H_2 and to 200 ppm CO interfering gas. In the third section, films are exposed to the interfering gas alone (200 ppm CO). For the $SiO_2-Co_3O_4$ nanocomposite film, CO slightly increases the film resistance in addition to resistance increase due to H_2 saturation as depicted in the second section of Fig. 5. This effect is totally absent for the SiO_2-NiO film. The lack of CO interfering effects may be explained in terms of a stronger affinity of the H_2 molecules to adsorb on the metal oxide surface (Cantalini, 2005).

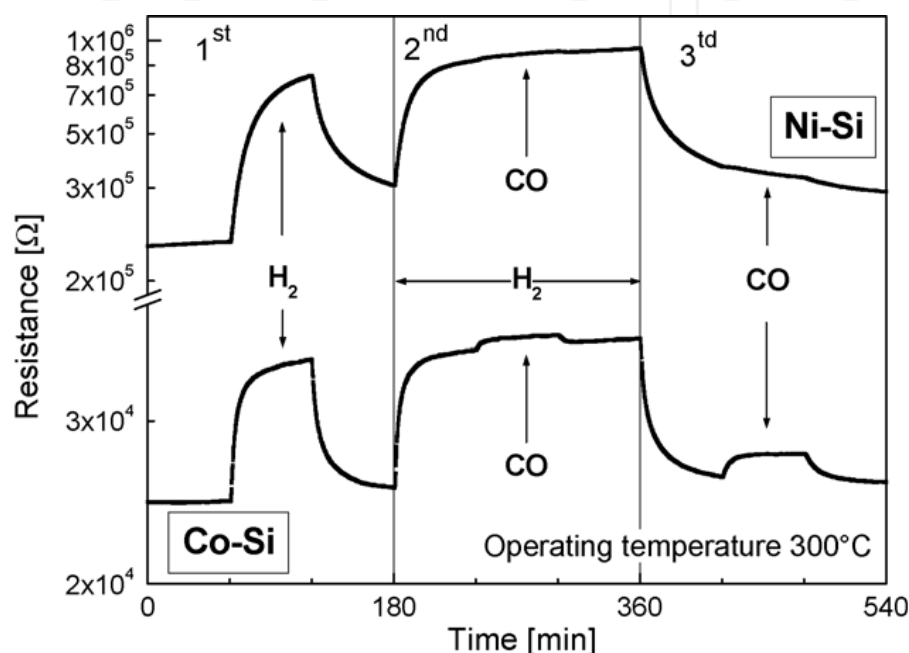


Fig. 5. Cross sensitivity test at 300 °C operating temperature of the SiO_2-NiO and the $SiO_2-Co_3O_4$ films to: (first section) 200 ppm H_2 in dry air; (second section) 200 ppm H_2 in dry air and 200 ppm CO; (third section) 200 ppm CO in dry air (Cantalini, 2005).

Martucci et al. (Martucci, 2004 & Martucci, 2003) has also studied the gas response of SiO_2-NiO and SiO_2-SnO_2 nanocomposite films for H_2 , CO and humidity at different operating temperatures ranging from 25 to 350°C and gas concentrations between 10 and 1000 ppm. SiO_2-NiO and SiO_2-SnO_2 nanocomposite films showed a p-type and n-type response, respectively, with greater sensitivity to H_2 gas than CO in the whole range of operating temperatures. The $NiO-SiO_2$ nanocomposite films also showed a reversible change in the optical transmittance in the VIS-NIR range when exposed to carbon monoxide gas.

Various TiO_2 based mixed oxide nanocomposite films, including TiO_2-WO_3 , TiO_2-MoO_3 , TiO_2-NiO_x , and TiO_2-ZnO , have been characterized for gas-sensing applications by Wisitsoraat et al. (Wisitsoraat, 2007). NiO_x addition to TiO_2 with sufficiently high concentration has produced a p-type semiconducting thin film while WO_3 , MoO_3 , and ZnO inclusions result in typical n-type metal oxide semiconductors. The gas-sensing sensitivity, selectivity, and minimum detectable concentration toward different gases including acetone, CO, and NO_2 can be effectively controlled by different dopants and doping concentrations. The p-type NiO_x doped TiO_2 showed high sensitivity towards ethanol and acetone with

distinct behaviours compared to other n-type TiO_2 thin films. Siriwong et al. (Siriwong, 2009) investigated WO_3 -doped ZnO composite containing 0.25, 0.50, and 0.75 mol% of WO_3 for NO_2 , CO and H_2 gas sensing at different gas concentrations and operating temperatures ranging from 300-400°C in dry air. Their results showed that WO_3 doping significantly enhanced NO_2 gas sensing performance of ZnO nanoparticles. In addition, 0.5 mol% is found to be an optimal WO_3 concentration which gives the highest sensitivity towards NO_2 . Other mixed oxides showing improved gas sensing properties include Cr_2O_3 - WO_3 films for NO_2 in NO_x mixtures (Cantalini, 2004), Fe_2O_3 -ZnO films for NH_3 (Tang, 2006) and $\text{CuO-Cu}_x\text{Fe}_{3-x}\text{O}_4$ (with $0 < x < 1$) for CO_2 (Chapelle, 2010).

4.3 Polymer-metal or metal oxide

Gas sensors using metal oxide films always lack in selectivity and require high operating temperatures (300-500°C). High operating temperatures may lead to sensor instability and response variation. Sensing materials with low operating temperatures can inhibit structural changes, reduce the power consumption and enable safer detection of combustible gases. Conducting polymers such as polypyrrole (PPy), polyaniline (PANI), polythiophene (PTh) and their derivatives typically can operate at low temperature in comparison to most of the metal oxide sensors. Conducting polymers can behave like semiconductors due to their heterocyclic compounds. As a result, reversible changes in the sensing polymer layer's conductivity can be detected upon adsorption of polar gas molecules on the surfaces at low temperature. This effect is believed to be caused by the charge transfer between gas molecules and the polymer or the polymer film's swelling. Conducting polymers are also easy to be synthesized through chemical or electrochemical processes, and their molecular chain structure can be modified conveniently by copolymerization or structural derivations. In addition, conducting polymers have good mechanical properties, which allow a facile fabrication of sensors. Conducting polymer matrices embedded with nano-scale metal or metal oxide particles form a new class of nanocomposite materials that has shown better gas sensing features. The reasons for such an improvement can be attributed either to catalytic behaviours of metal particles or to the formation of metal oxide-polymer junction. For example, the n-type SnO_2 forms a hetero pn-junction to p-type conducting polymer with a depletion region. The gas adsorption causes a change in depletion region and thus modulates the conductivity of the junction. Other non-conductive polymers such as fluorocarbon films swell when exposed to the vapours of organic solvents having a net dipole moment or electron-rich moieties therefore can also be used as active materials for the gas sensing. Addition of metal or carbon to those polymers was found to improve their swell sensitivity.

Fabrication

Metal-polymer nanocomposites can easily be prepared by PVD processes such as sputter deposition and vacuum thermal evaporation, as well as wet chemical deposition. For example, Tiwari et al. (Tiwari, 2009, & 2010) used vacuum thermal evaporation of poly(o-phenylenediamine) (PoPD)/ $\text{WO}_3 \cdot n\text{H}_2\text{O}$ mixed powder pellet to fabricate nanocomposite films of PoPD- $\text{WO}_3 \cdot n\text{H}_2\text{O}$ on an indium tin oxide (ITO) coated glass surface for NO_2 gas sensor applications. Using the same method; they also prepared aniline-formaldehyde condensate (AFC)- $\text{WO}_3 \cdot n\text{H}_2\text{O}$ nanocomposite films. The mixed powder pellets were formed via hydraulically pressing of nanocomposite powders which was prepared by in situ condensation reaction of PoPD or AFC in the presence of sodium tungstate. The composite

thin films exhibited a crystalline surface morphology containing nanocrystals of $\text{WO}_3 \cdot n\text{H}_2\text{O}$ with a diameter ranging from 5 to 20 nm. Cioffi et al. prepared gold-fluorocarbon (Au-CF_x) and palladium-fluoropolymer (Pd-CF_x) nanocomposites films on silicon substrates by co-sputtering a Teflon and a gold targets or a Teflon and a palladium targets, respectively, with Ar^+ ion beams (Cioffi, 2002 & 2004).

Wet-chemical deposition route can also be used to prepare polymer-metal oxide nanocomposite films, for example, tin oxide-intercalated polyaniline nanocomposite have been deposited at room temperature by Deshpande et al. (Deshpande, 2009) through the following procedure: $\text{SnCl}_4 \cdot 5\text{H}_2\text{O}$ was first hydrolyzed at $\text{pH} \leq 4$ using dilute HCl . Hydrogen peroxide was added to the solution to oxidize tin ions to form tin oxide suspension. The suspension solution was mixed with aniline and $(\text{NH}_4)_2\text{S}_2\text{O}_8$. Pre-cleaned glass substrates were inserted vertically into the solution for the growth of the nanocomposite film on the substrate. Tin oxide exists as nanoparticles form in the polyaniline (PANI) matrix in the composite films. Intercalation reactions is another wet-chemical process used to prepare polymer-metal oxide nanocomposite, for example, polypyrrole (PPy)- MoO_3 nanocomposite thin films have been prepared by the intercalation reactions of highly oriented MoO_3 thin films with the following procedure: hydrated sodium ions were inserted into the CVD grown MoO_3 thin films on LaAlO_3 (100) single crystal substrates to give $[\text{Na}(\text{H}_2\text{O})_2]_y\text{MoO}_3$ films. The obtained $[\text{Na}(\text{H}_2\text{O})_2]_y\text{MoO}_3$ thin films then reacted with an excess amount of pyrrole and oxidizing agent (FeCl_3) to form the $(\text{PPy})_x\text{MoO}_3$ thin films. Intercalation of hydrated sodium ions successfully proceeded without losing the crystallographic orientation. The $(\text{PPy})_x\text{MoO}_3$ thin films can detect formaldehyde gas by increasing their electrical resistance, whereas they showed no response to toluene (Hosono, 2004). Tai et al. (Tai, 2007 & 2008) reported using simultaneous polymerization of aniline monomer and oxidation of PANI molecules in an active solution contained colloidal TiO_2 , aniline monomer, HCl and oxidizing agent ammonium persulfate ($(\text{NH}_4)_2\text{S}_2\text{O}_8$) to fabricate the polyaniline-titanium dioxide (PANI-TiO_2) nanocomposite films for NH_3 gas-sensing application.

Unique properties

Polymer-metal or metal oxide nanocomposite is a new class of material that combines the advantages of both organic polymer material and inorganic metal or semiconductor oxide and shows improved optical, electrical and mechanical properties for gas sensor applications. Cioffi et al. (Cioffi, 2004) investigated $-\text{CF}_x$ polymer films embedded with Pd or Au nanoparticles (Pd-CF_x and Au-CF_x nanocomposites films) for detecting vapours of organic solvents. They found that Pd-CF_x and Au-CF_x nanocomposites films swell more significantly than pure $-\text{CF}_x$ film when exposed to the vapours of organic solvents having a net dipole moment or electron-rich moieties such as acetone, chloroform, 2-propanol. Ellipsometric evaluation of the thickness changes of $-\text{CF}_x$ and metal- CF_x films when they exposed to an increasing concentration of acetone vapours was shown in Fig. 6(a). All the films show almost linear dependence of the thickness change upon the analyte concentration but $-\text{CF}_x$ swelling sensitivity is much less pronounced than that of the metal- CF_x composites. Acetone-induced swelling of both Au-CF_x and Pd-CF_x materials increases as the metal loading increases and the swelling response of Pd-CF_x films is higher than that of Au-CF_x of the same metal loading. TEM surface morphology of the Pd-CF_x film with a metal loading of 0.15 and 10 nm thick is shown in Fig. 6(b). TEM graphs revealed a regular, non-porous Pd-CF_x film structure with homogeneous distribution of palladium

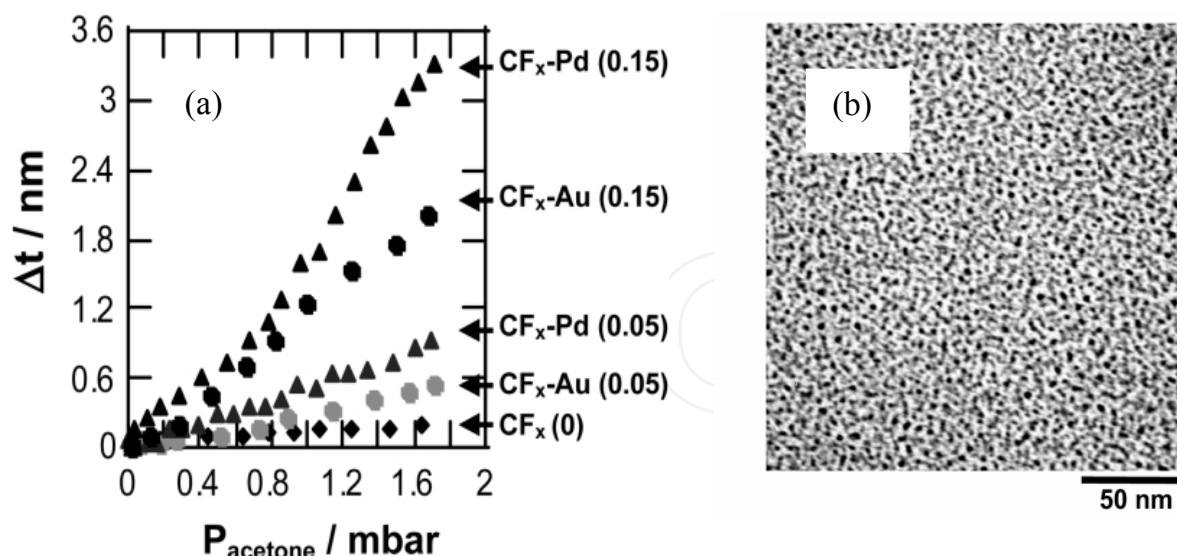


Fig. 6. (a) Acetone-induced thickness variations (Δt) of Pd- CF_x , Au- CF_x and CF_x layers (metal volume fractions are in brackets) upon exposure to increasing partial pressures of the organic solvent measured by ellipsometry; (b) TEM micrographs of Pd- CF_x films with metal loading of 0.15 (Cioffi, 2004).

nanoparticles. The mean diameter of the palladium nanoparticles is 2.9 ± 0.6 nm. The morphological similarities exist between Pd- CF_x and Au- CF_x films of same metal volume fraction. Differences in the materials sensing performances are ascribed to different chemical reactivity and selectivity of Pd and Au. Swelling behaviour of poly(2-hydroxyethyl methacrylate) (PHEMA)-carbon black nanocomposites was also investigated by Mauro et al (Mauro, 2009) for volatile organic compounds (VOCs) detection using white light interferometry. They demonstrated that swelling in the range of only a few nanometers can be measured and the PHEMA-C nanocomposite undergoes a more pronounced swelling process than PHEMA itself.

Polyaniline (PANI) is a conducting polymer with high electrical conductivity. Due to its ease of synthesis, environmental stability, and response to acid/base doping, it was thoroughly studied for its application as an active material for gas sensors. Mixing semiconductive metal oxide with PANI to form nanocomposites was found to be an effective way to improve the gas sensing properties of PANI. Tai et al. (Tai, 2007) studied a polyaniline-titanium dioxide (PANI- TiO_2) nanocomposite films for the NH_3 gas sensor. They found that the nanocomposite exhibited higher sensitivity, faster response and recovery rates to NH_3 than those of pure PANI thin film sensors fabricated under identical conditions. They found that the TiO_2 components influenced the morphology of the nanocomposite film, which led to the variation of the sensor response-recovery behaviours. Deshpande et al (Deshpande, 2009) discovered that good sensitivity; reproducibility and faster response to NH_3 at room temperature can be achieved by using SnO_2 -PANI nanocomposites films while under the same conditions pure SnO_2 films remain inert. They found that resistance of the nanocomposite (SnO_2 -PANI) films decreases while pure PANI film resistance increases when exposed to NH_3 indicating SnO_2 doping totally changed the electrical property of PANI. PANi- In_2O_3 was another PANI-oxide nanocomposite films that was thoroughly investigated. The nanocomposite film based gas sensor was fabricated on AT-Cut quartz crystal microbalance (QCM) and its sensitive properties to CH_4 and CO were characterized.

They found that PANi-In₂O₃ thin film has good linear sensitive property to CH₄ and CO, and it is more sensitive to CH₄ than CO (Yan, 2009). Misra et al. (Misra, 2004) studied the Fe-Al doped nanocomposite copolymer of aniline and formaldehyde and found that the nanocomposite exhibits high stability, sensitivity, selectivity and a fast response towards the HCl vapours in the air at room temperature. Optimization of doping (Fe-Al) level in nanocomposite copolymer during synthesis can improve the sensing properties.

Other polymer nanocomposite films that were investigated for gas sensor applications include TiO₂-porphyrin film coated on a quartz crystal to detect volatile organic compounds such as ethanol, acetone, 2-propanol, cyclohexane, toluene and o-xylene (Arshad, 2008); poly(vinyl butyral)-carbon black films prepared for methanol, propanol and hexanol vapour (Arshak, 2006); sodium polystyrenesulfonate (NaPSS)-ZnO for humidity sensors (Yang, 2002); polypyrrole (PPy)-SnO₂, PEDT-SnO₂, PHTH-SnO₂ and copolymer (HTH-EDT)-SnO₂ films for NO₂ gas sensing applications (Ram, 2005); poly(3-hexylthiophene)-ZnO films for NO₂, NH₃, CO and ethanol detection (Baratto, 2006); PoPD-WO₃.nH₂O (Tiwari, 2009) and AFC-WO₃.nH₂O (Tiwari, 2010) films for NO₂ gas sensing.

4.4 Carbon nanotube based nanocomposite films

Carbon nanotubes (CNTs) are very useful materials for gas-sensing applications because of their high surface to volume ratio. The large surface area provided by the hollow cores and outside walls in nanotubes gives them very large capacity for gas absorption. Interaction of CNTs with certain gases can change the electrical properties of semiconducting CNTs even at room temperature. However, CNTs based sensor has a number of limitations including long recovery time, and weakness to humidity. In addition, the range of gas molecules that can be detected by CNTs sensors is limited to the molecules that have large binding energies and charge transfers with the CNTs. To improve the gas sensing properties of CNTs, catalytic metal nanoparticles, semiconductive metal oxides or conductive polymers were mixed with CNTs to form nanocomposites. The composite combines the advantages of CNTs and other gas-sensing materials and provide a new class of active materials with unique gas sensing property.

Fabrication

CNTs nanocomposite films can be prepared by combining CVD and PVD processes. For example, Pt-, Ru- and Ag-nanoclusters embedded CNTs nanocomposites were prepared by RF magnetron sputtering and RF-discharge plasma enhanced chemical vapour deposition (PECVD) processes in the following steps: First, iron catalyst film of 2.5 nm thick was deposited by RF magnetron sputtering on alumina substrates using Ar flux of 43 sccm, process pressure of 1.2×10^{-2} Torr and RF power of 150 W. The PECVD iron film was used for the subsequent CNTs growth at a substrate temperature of 600°C with 20/80 sccm C₂H₂/H₂ flow and total pressure of 1.5 Torr. The carbon nanotubes obtained were "forest-like" with ropes vertically-aligned to the substrate surface. CNTs surface has been subsequently modified by depositing 5 nm thick Pt-, Ru- and Ag nanoclusters. The Field emission SEM images of the metal-coated CNTs are shown in Fig. 7(a), (b), and (c), respectively. The metal-catalysts deposited onto the surface of the forest-like CNTs network existed as dispersed islands with non-uniform distribution. To drive metal nanoparticles diffuse into the inside of the CNT-forest, thermal treatment was used. The diameters of metal cluster are ranging from 3 nm for platinum and ruthenium (Fig. 7(a) (c)), to 50 nm for Ag (Fig. 7 (b)), which depend on the reactivity between metal and graphite surface (Penza,

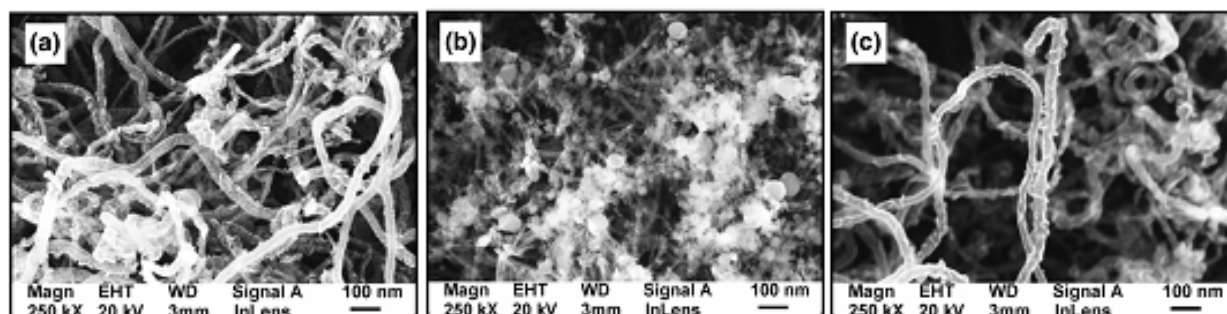


Fig. 7. FE-SEM images of the CNT films surface-functionalized with (a) platinum (Pt), (b) silver (Ag) and (c) ruthenium (Ru) nanoclusters (Penza, 2009).

2009). Wisitsoraat et al. (Wisitsoraat, 2006) used electron beam evaporation of cylindrical pellets consisting of pressed multi-wall CNTs (MWCNTs) mixed with SnO_2 powder to form CNTs- SnO_2 nanocomposite films. The CNTs were synthesized by chemical vapour deposition using acetylene and argon gases with iron catalyst at 600 °C. The substrates for thin film coating were standard BK7 glass slides.

Sol-gel process can also be used to prepare CNTs nanocomposites. For example, antimony-CNTs-tin oxide nanocomposite films were prepared with the following procedure: tin(IV) chloride pentahydrate ($\text{SnCl}_4 \cdot 5\text{H}_2\text{O}$) was dissolved in ethanol as the precursor solution for the sol. After being mixed with antimony (III) chloride (SbCl_3), a certain amount of CNTs with weight percentage of 1-10 wt % to SnO_2 was dispersed into the former solution by ultrasonic dispersing. The CNTs with diameter from 6 to 8 nm were obtained via catalytic CVD process. The final sol was dip-coated onto a substrate. The as-fabricated sensor samples were dried for the formation of crack-free thin films. Subsequently, the samples were calcined in air at 500°C, the dip-coating and drying operation steps were carried out repeatedly to increase the film thickness (Liu, 2008). Duy et al. (Duy, 2008) also used the sol-gel process to prepare CNTs- SnO_2 - TiO_2 nanocomposite films. The precursors used to fabricate the SnO_2 - TiO_2 sol were tetrapropylorthotitanate $\text{Ti}(\text{OC}_3\text{H}_7)_4$, tinethylhexanoate $\text{Sn}(\text{OOC}_7\text{H}_{15})_2$ and isopropanol $\text{C}_3\text{H}_7\text{OH}$. To synthesize the CNTs- SnO_2 - TiO_2 composite material, the single-walled CNTs (SWCNTs) with a diameter less than 2 nm and MWCNTs with diameters ranging from 20 to 40 nm were introduced and dispersed into the SnO_2 - TiO_2 sol solution by an ultrasonic shaker. The film was deposited by spin coating on silica substrate with Pt-interdigitated electrode and was dried at 60 °C and annealed at 500°C. The inclusion of CNTs did not affect the particle size as well as the morphology of the oxides. The sensing properties of those CNTs-oxides sensors towards different ethanol concentrations and operating temperatures were investigated (Duy, 2008). Other sol-gel fabricated CNTs nanocomposite films include SWNTs- SnO_2 film for hydrogen detection (Gong, 2004); and MWNTs- SiO_2 for methane, hydrogen and acetylene sensing (Xin, 2005).

Unique properties

CNTs mixed with catalytic metal nanoparticles have been found to significantly improve gas sensing properties of CNTs. The Pt-, Ru- and Ag-CNT nanocomposites prepared by RF magnetron sputtering and PECVD as described previously in Fig. 7 was investigated for NO_2 gas by Penza et al. and the results are shown in Fig. 8. Fig. 8(a) and (b) shows the response curves of those nanocomposite films at a sensing temperature of 25°C and 150°C, respectively.

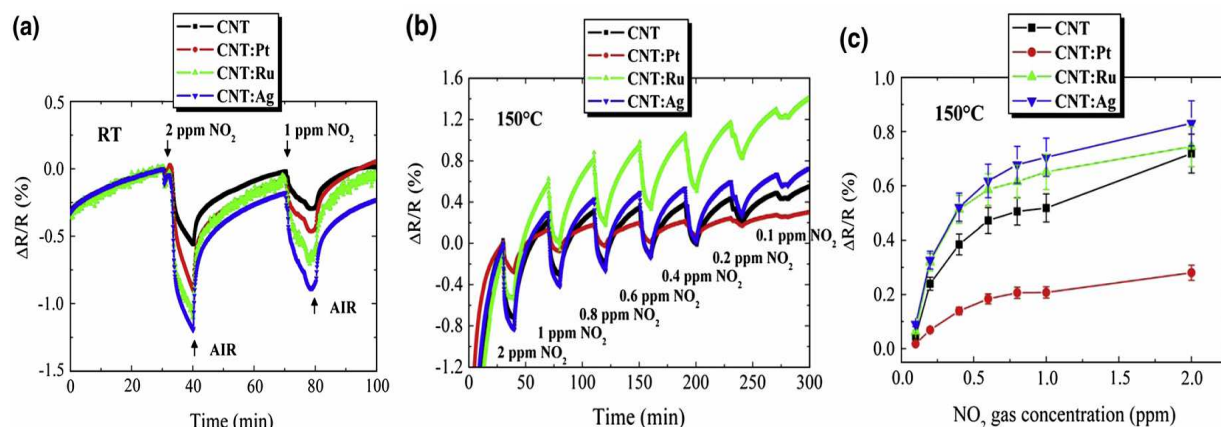


Fig. 8. (a) Response of CNTs-metal nanocomposite chemiresistors towards NO_2 gas. The thickness of metal-catalyst and CNT layer is 5 nm and 10 μm , respectively. (b) Time response towards NO_2 gas of the CNT-metal nanocomposite chemiresistors at sensor temperature of 150 $^{\circ}\text{C}$. (c) Calibration curves, at 150 $^{\circ}\text{C}$ (Penza, 2009).

With comparison to unmodified CNTs, the enhanced response of Pt-, Ru- and Ag nanocluster coated vertically-aligned CNTs layer towards the NO_2 gas was clearly observed at both temperatures as shown in Fig.8 (a) and (b). The minimum gas detection of 0.1 ppm NO_2 was achieved at 150 $^{\circ}\text{C}$ for metal coated CNTs. The calibration curves at 150 $^{\circ}\text{C}$ for unmodified and coated CNTs films are shown in Fig. 8(c). The maximum NO_2 gas response was achieved by Ag-coated CNTs. The metal coated CNTs films also significantly enhanced gas detection of H_2 , ethanol and toluene up to sub-ppm level that makes metal-CNTs nanocomposites highly promising candidates for environmental air monitoring applications (Penza, 2009). Brahim et al. has also investigated metal-carbon nanotubes (CNTs) nanocomposite materials as the active sensing layer for ethanol vapour detection at room temperature. They found that pure CNTs material was virtually non-responsive at low ethanol concentrations (< 50 ppm), while the metal-CNT composite films (Ti-, Mn-, Fe-, Co-, Pd- or Pt-CNTs) showed extremely high sensitivity to trace ethanol levels with 100-fold or more gains in sensitivity relative to the pure SWNTs (Brahim, 2009).

By mixing semiconductive metal oxides such as SnO_2 with CNTs, the gas sensing properties of the oxides can also be improved. For example, Sb-CNTs- SnO_2 thin film shows higher sensitivity and shorter response time than pure SnO_2 and Sb- SnO_2 thin films for sensing polar gases, such as formaldehyde, ammonia, and toluene as shown in Fig. 9. The figure shows the response of pure oxides and CNTs-oxide nanocomposite films when they were exposed to target gases or dry air alternately. The voltage increased when the target gas was injected and decreased as dry air was introduced. The sensitivity of the Sb-CNTs- SnO_2 thin film is higher among the three films. The response time of the Sb-CNTs- SnO_2 thin film is also significantly shorter. CNTs addition was believed to affect the grain growth and surface area of SnO_2 as well as create CNTs-Oxide interfacial region which improves the gas sensing properties (Liu, 2008). CNTs doped SnO_2 film was also investigated by Wisitsoraat et al. (Wisitsoraat, 2006) for ethanol sensing and they found that SnO_2 -CNTs nanocomposite can operate with good sensitivity and stability at a relatively low temperature of 250-300 $^{\circ}\text{C}$.

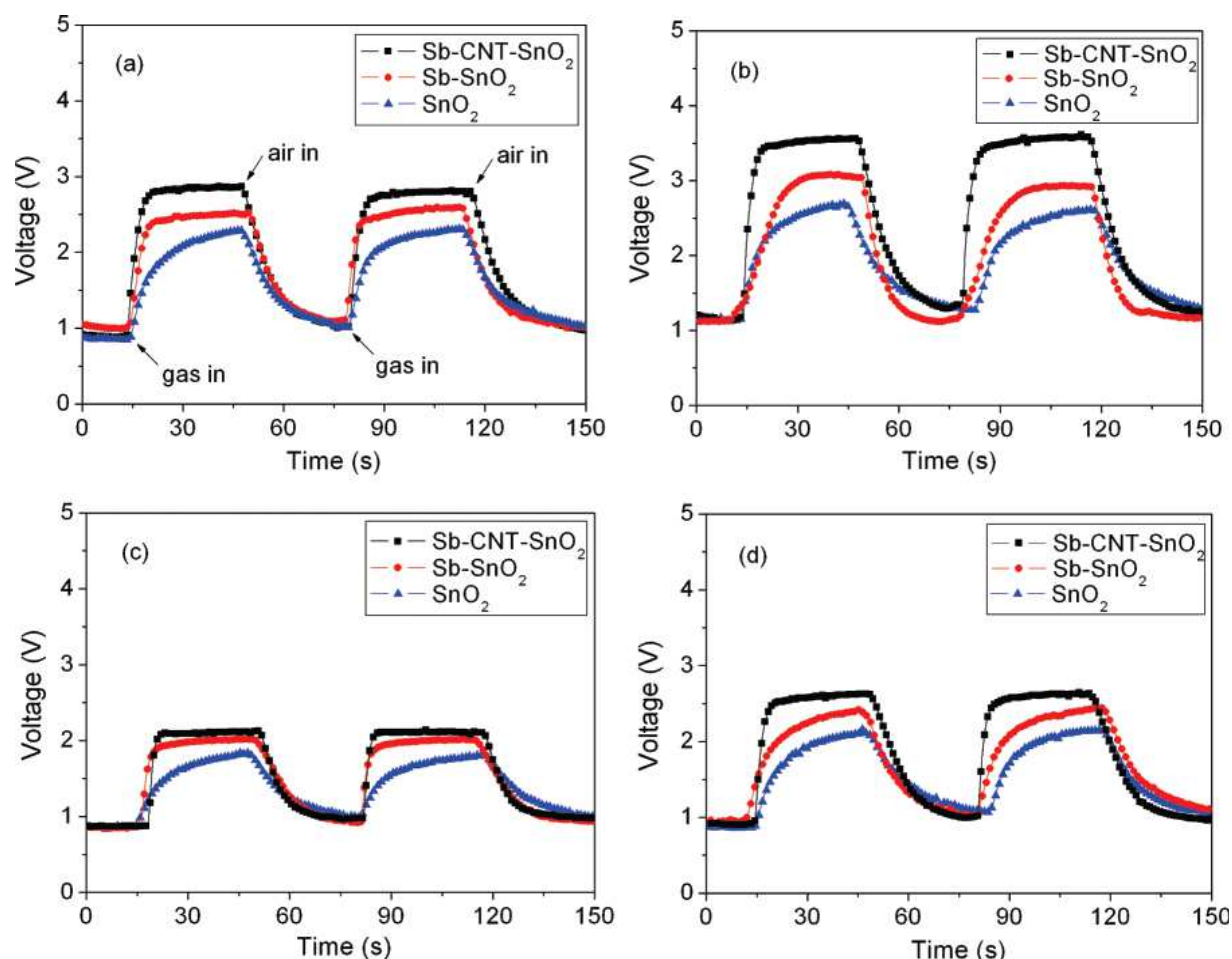


Fig. 9. Gas sensing response of SnO_2 , Sb-SnO_2 and Sb-CNTs-SnO_2 thin films to (a) formaldehyde, (b) ammonia, (c) benzene, and (d) toluene (Liu, 2008).

The improved gas-sensing properties were attributed to the increasing in surface area of metal oxide induced by CNTs protrusion. The sensitivity to ethanol of CNTs incorporated SnO_2 thin film was found to increase by the factors of 3 to 7 with CNTs inclusion up to 2%. In addition, the response time and recovery time were found to reduce by the factors of 2 or more. However, they also found that if the CNTs concentration is too high, the sensitivity is decreased. Bhuiyan et al. (Bhuiyan, 2008) also observed higher sensitivity and lower operating temperature for SnO_2 -SWCNTs nanocomposite films than the pure CNTs or SnO_2 films for the detection of NO and NO_2 gas in the carrier gas nitrogen (N_2) or air. CNTs- SnO_2 films were also investigated by Wisitsoraat et al. (Wisitsoraat, 2007) for sensing ethanol, CO and NO_2 , and by Gong et al. for sensing H_2 . Wisitsoraat found that 1% CNT- SnO_2 exhibit maximized response to NO_2 with sensitivity of ~ 10 at NO_2 concentration as low as 250 ppb at 200°C , while Gong found that nanocomposite films have greater sensitivity (a factor of 3), faster response time and recovery time, and less drift in resistance measurement for H_2 sensing. Small amount of CNTs incorporation into SnO_2 proved to be an effective means to enhance gas-sensing sensitivity of semiconductive metal oxide sensors. The improved sensitivity is credited to the large surface to volume ratio of gas sensing film with nano

passes created by CNTs. Other metal oxides that were used to composite with CNTs include SiO_2 and ZnO . Xin et al. (Xin, 2005) found that MWNTs- SiO_2 composite film was sensitive to methane, hydrogen and acetylene while the pure MWNTs was not. They believed that MWNTs and silicon dioxide formed the Schottky junctions. Adsorption of the gas molecules on the surface of the MWNTs affects the space discharge area of the Schottky junction, so that the dielectric constant of nanocomposite films changes with the gas adsorption. ZnO -SWNTs fabricated by oxidizing metallic zinc deposited on a SWNTs template also showed higher sensitivity and lower operating temperature than the zinc oxide film for hydrogen gas sensing (Jung, 2008).

Polymers can also be used to modify CNTs to improve its sensing properties. For example, PMMA-MWCNTs nanocomposite shows fast response and change in resistance upon exposure to different organic vapours. The room temperature gas sensing property of MWCNTs-PMMA nanocomposite makes it very attractive for miniature wireless gas sensor applications. The sensing mechanism of MWCNTs-PMMA films to organic solvents was attributed to the swelling of the polymer matrix due to the absorption of organic vapours which increases the volume and the distance between the nanotubes. The contact resistance between adjacent CNTs thus increases as their distance increase. The extent of swelling and hence the electrical response depends on the solubility of the polymer in the solvent. In addition, CNT surface that contains polar functional groups can also adsorb organic solvent molecules (Abraham, 2004). Hieu et al. investigated the effects of film thickness, annealing temperature, and SWCNTs content on gas-sensing response of PPY-SWCNTs nanocomposite for detection of NH_3 gas at room temperature. They found that the nanocomposite sensor had a response of 26-276% upon exposure to NH_3 gas concentration from 10 to 800 ppm, and their response and recovery times were around 22 and 38 s, respectively (Hieu, 2009). All the above results clearly indicate that by properly mixing metal or metal oxide with CNTs to form nanocomposites, higher sensitivity and lower operating temperature than that of pure metal oxide or CNTs films for gas sensing can be achieved.

5. Conclusion and future directions

Nanocomposite thin film-based gas sensors have been developed and demonstrate huge potential for a variety of applications such as drug, food and environmental monitoring. Different types of nanocomposite thin films can be fabricated by various deposition processes such as PVD, CVD, sol-gel, and other wet-chemical synthesis. It has been proved that the electrical resistance, sensitivity, selectivity, response time and operating temperature of gas sensors can be significantly improved by using nanocomposite films as the active sensing materials. This can be attributed to the complementary behaviours of the consisting materials, the unique interface characteristics and large surface areas, as well as nano-scale dimensional effects. Chemoresistors that measure the resistance change of nanocomposite films as the transducer is the most commonly used sensor structures. Compared to chemoresistors sensors, optical sensors present a number of advantages such as enabling multi-parametric detection, no need for electrical contacts, do not suffer from electromagnetic noise, allow optoelectronic integration and have the potential of multi-gas detection. Optical sensors using SPR response of nanocomposite films that consist of

metallic nanoparticles embedded in metal oxide or polymer matrix are of great interest and should be further explored. Acoustic wave sensors are most suitable for polymer based nanocomposites as they can precisely measure the thickness variation when polymers swell after their exposure to the vapours of organic solvents.

Although nanocomposite films have demonstrated their great potential for gas sensor applications, several challenges still remain. Synthesis of nanocomposite films with precisely controlling their chemical composition ratio, micro/nanostructures, phases, surface area and interfacial characteristics is still a challenging task. Depending on the preparation technique and process parameters, the property and behaviours of the nanocomposite sensors can vary significantly; therefore, the ability to reproduce nanocomposite films with consistent properties is very important for their wide use as active sensing materials. Degradation of the nanocomposite films stemming from aggregation of the nanosized components due to relatively strong inter-particle forces between them, micro/nanostructure changes due to high operating temperatures and surface contaminations due to impurity etc. has to be resolved before their large-scale adoption by the industry. With the increased interests and intensive research and development in the field, it is expected that, nanocomposite thin film gas sensors will have a promising future and will make a major impact on the gas sensor industry.

6. References

- Abraham, J. K.; Philip, B.; Witchurch, A.; Varadan V. K. and Reddy, C. C. (2004). A compact wireless gas sensor using a carbon nanotube/PMMA thin film chemiresistor. *Smart Materials and Structures* 13(5): 1045-1049.
- Arshad, S.; Salleh, M. M.; and Yahaya, M. (2008). The performance of quartz crystal microbalance coated TiO₂-porphyrin nanocomposite thin film gas sensors. *Sensor Letters* 6(6): 903-907.
- Arshak, K. I.; Cavanagh, L. M.; and Cunniffe, C. (2006). Excess noise in a drop-coated poly(vinyl butyral)\carbon black nanocomposite gas sensitive resistor. *Thin Solid Films* 495(1-2): 97-103.
- Brahim, S.; Colbern, S.; Gump, R.; Moser, A. and Grigorian L. (2009). Carbon nanotube-based ethanol sensors. *Nanotechnology* 20(23): 235502.
- Baratto, C.; Faglia, G.; Ferroni, M.; Sberveglieri, G. (2006). Investigation on novel poly (3-hexylthiophene)-ZnO nanocomposite thin films gas sensor. *Proceedings of IEEE Sensors. 2006 5th IEEE Conference on Sensors*. (pp 452-455), 2006. Article Number: 4178655.
- Bhuiyan, M. M. H.; Katsuki, S.; Ueda, T.; Ikegami, T. (2008). Improvement in the sensitivity of SnO₂ thin film based NO_x gas sensor by loading with single-walled carbon nanotube prepared by pulsed laser deposition process. *Sensor Letters*, vol 6(4) (pp 635-640), 2008.
- Bubb, D. M.; McGill, R. A.; Horwitz, J. S.; Fitz-Gerald, J. M.; Houser, E. J.; Stroud, R. M.; Wu, P. W.; Ringeisen, B. R.; Piqué, A. and Chrise, D. B. (2001). Laser-based processing of polymer nanocomposites for chemical sensing applications. *Journal of Applied Physics* 89(10): 5739-5746.

- Buso, D.; Post, M.; Cantalini, C.; Mulvaney, P. and Martucci A. (2008). Gold Nanoparticle-Doped TiO_2 Semiconductor Thin Films: Gas Sensing Properties, *Advanced Functional Materials*. Vol. 18, no. 23, pp. 3843-3849. 8 Dec. 2008, Wiley-VCH Verlag GmbH, P.O. Box 10 11 61, Weinheim, D-69451, Germany.
- Cantalini, C. (2004). Cr_2O_3 , WO_3 Single and Cr/W Binary Oxide Prepared by Physical Methods for Gas Sensing Applications. *Journal of the European Ceramic Society* 24(6): 1421-1424.
- Cantalini, C.; Post M.; Buso, D.; Guglielmi, M. and Martucci, A. (2005). Gas sensing properties of nanocrystalline NiO and Co_3O_4 in porous silica sol-gel films. *Sensors and Actuators, B: Chemical* 108(1-2 SPEC. ISS.): 184-192.
- Chapelle, A.; Oudrhiri-Hassani, F.; Presmanes, L.; Barnabé, A. and Tailhades, Ph. (2010). CO_2 sensing properties of semiconducting copper oxide and spinel ferrite nanocomposite thin film. *Applied Surface Science* 256(14): 4715-4719
- Cioffi, N.; Farella, I.; Torsi, L.; Valentini, A. and Tafuri, A. (2002). Correlation between surface chemical composition and vapour sensing properties of gold-fluorocarbon nanocomposites. *Sensors and Actuators, B: Chemical* 84(1): 49-54.
- Cioffi, N.; Torsi, L., Farella, I.; Altamura, D.; Valentini, A.; Ditaranto, N.; Sabbatini, L.; Zambonin, P. G. and Bleve-Zacheo, T. (2004). Deposition and analytical characterization of fluoropolymer thin films modified by palladium nanoparticles. *Thin Solid Films*, 449(1-2): 25-33.
- Della Gaspera, E.; Guglielmi, M.; Agnoli, S.; Granozzi, G.; Post, M. L.; Bello, V.; Mattei G. and Martucci, A. (2010). Au nanoparticles in nanocrystalline TiO_2 -NiO films for SPR-based, selective H_2S gas sensing. *Chemistry of Materials* 22(11): 3407-3417.
- Deng, H.; Yang, D.; et al. (2008). Simulation of surface plasmon resonance of Au- WO_{3-x} and Ag- WO_{3-x} nanocomposite films. *Sensors and Actuators, B: Chemical* 134(2): 502-509.
- Deshpande, N. G.; Gudage, Y. G.; Sharma, R.; Vyas, J.C.; Kim, J.B. and Lee, Y.P. (2009). Studies on tin oxide-intercalated polyaniline nanocomposite for ammonia gas sensing applications. *Sensors and Actuators, B: Chemical* 138(1): 76-84.
- Duy, N. Van; Van Hieu, N.; Huy, P. T.; Duc Chien, N. ; Thamilselvan, M. and Yi, Junsin. (2008). Mixed $\text{SnO}_2/\text{TiO}_2$ included with carbon nanotubes for gas-sensing application. *Physica E: Low Dimensional Systems and Nanostructures* 41(2): 258-263.
- Fernandez, C. d. J.; Manera, M. G.; Spadavecchia, J.; Buso, D.; Pellegrini, G.; Mattei, G. and Martucci, A.; Rella, R.; Vasanelli, L.; Guglielmi, M. and Mazzoldi, P. (2005). Gold/titania nanocomposites thin films for optical gas sensing devices. SO: *Source Proc. SPIE.*, Vol. SPIE-5116, pp. 703-710. 2005.
- Gong, J. and Chen, Q. (2004). Sol-gel prepared single wall carbon nanotube SnO_2 thin film for micromachined gas sensor. 2004 NSTI Nanotechnology Conference and Trade Show - NSTI Nanotech 2004, Boston, MA.
- Gong, J.; Chen Q.; Lian, M.-R. and Liu, N.-C. (2005). Micromachined nanocrystalline silver doped tin oxide hydrogen sulfide sensor. *Nanotech 2005 Technical Proceedings*, 2005 NSTI Nanotechnology Conference and Trade Show - NSTI, Anaheim, CA.

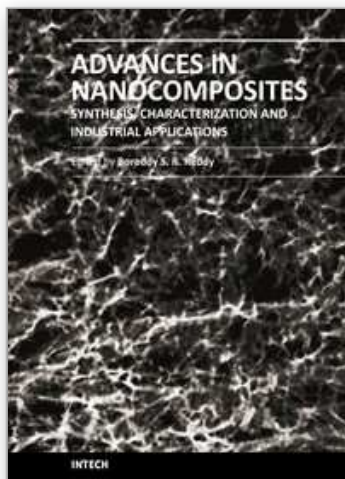
- Gong, J.; Chen Q.; Lian, M.-R.; Liu, N.-C.; Stevenson, R. G.; and Adami Fatos (2006). Micromachined nanocrystalline silver doped SnO₂ H₂S sensor. *Sensors and Actuators, B: Chemical*, 114(1): 32-39.
- Gu, Z.; Liang P.; Zhang, W. (2006). Sol-gel derived Sb-doped SnO₂/ SiO₂ Nano-composite thin films for gas sensors. *Proceedings of SPIE - The International Society for Optical Engineering*, Zvenigorod.
- Qureshi, A.; Mergen, A.; and Altindal, A. (2009). Preparation and characterization of Li and Ti codoped NiO nanocomposites for gas sensors applications. *Sensors and Actuators, B: Chemical* 135(2): 537-540.
- Gyorgy, E.; Giannoudakos, A.; Kompitsas M. and Mihailescu I. N. (2008). Laser grown gold nanoparticles on zinc oxide thin films for gas sensor applications. *Journal of Optoelectronics and Advanced Materials* 10(3): 536-540.
- Hieu, N.; Dung, N. Q.; Tam, P. D.; Trung, T. and Chien, N. D. (2009). Thin film polypyrrole/SWCNTs nanocomposites-based NH₃ sensor operated at room temperature. *Sensors and Actuators, B: Chemical* 140(2): 500-507.
- Jung, J.; Song, H.; Kang, Y.; Oh, D.; Jung, H.; Cho, Y.; Kim, D. (2008). Hydrogen sensing properties of ZnO-SWNTs composite. *Korean Journal of Materials Research* 18(10): 529-534.
- Kaushik, A.; Khan, R.; Gupta, V.; Malhotra, B.D.; Ahmad, S.; Singh, S.P. (2009). Hybrid cross-linked polyaniline-WO₃ nanocomposite thin film for NO_x gas sensing. *Journal of Nanoscience and Nanotechnology*. vol 9(3) (pp 1792-1796), 2009
- Korotcenkov, G.; Cho, B. K.; Gulina, L. and Tolstoy, V. (2009). SnO₂ thin films modified by the SnO₂-Au nanocomposites: Response to reducing gases. *Sensors and Actuators, B: Chemical* 141(2): 610-616.
- Kotsikau, D.; Ivanovskaya, Orlik, M.; D. and Falasconi, M. (2004). Gas-sensitive properties of thin and thick film sensors based on Fe₂O₃-SnO₂ nanocomposites. *Sensors and Actuators, B: Chemical* 101(1-2): 199-206.
- Li, D.; Jiang, Y.; Wu, Z.; Chen, X. and Li, Y. (2000). Self-assembly of polyaniline ultrathin films based on doping-induced deposition effect and applications for chemical sensors. *Sensors and Actuators, B: Chemical* 66(1): 125-127.
- Li, Y. X.; Galatsis, K.; Wlodarski, W.; Passacantando, M.; Santucci, S.; Siciliano, P. and Catalano, M. (2001). Microstructural characterization of MoO₃-TiO₂ nanocomposite thin films for gas sensing. *Sensors and Actuators, B: Chemical* 77(1-2): 27-34.
- Liu, J.; Guo, Z.; Meng, F.; Jia, Y. and Liu, J. (2008). A novel antimony - Carbon nanotube-tin oxide thin film: Carbon nanotubes as growth guider and energy buffer. Application for indoor air pollutants gas sensor. *Journal of Physical Chemistry C* 112(15): 6119-6125.
- Manera, M. G.; Spadavecchia, J.; Buso, D.; Fernández, C. de Julián; Mattei, G.; Martucci, A.; Mulvaney, P.; Pérez-Juste, J.; Rella, R.; Vasanelli, L. and Mazzoldi, P. (2008). Optical gas sensing of TiO₂ and TiO₂/Au nanocomposite thin films. *Sensors and Actuators, B: Chemical* 132(1): 107-115.

- ^aMartucci, A., Bassiri, N.; Guglielmi, M.; Armelao, L.; Gross, S. and Pivin, J.C. (2003). NiO-SiO₂ sol-gel nanocomposite films for optical gas sensor. *Journal of Sol-Gel Science and Technology* 26(1-3): 993-996.
- ^bMartucci, A.; Pasquale, M.; Martucci, A.; Pasquale, M.; Guglielmi, M., Post, M. and Pivin, J. C. (2003). Nanostructured silicon oxide-nickel oxide sol-gel films with enhanced optical carbon monoxide gas sensitivity. *Journal of the American Ceramic Society* 86(9): 1638-1640.
- Martucci, A.; Buso, D.; Monte, M. D.; Guglielmi, M.; Cantalini, C. and Sada C. (2004). Nanostructured sol-gel silica thin films doped with nio and sno₂ for gas sensing applications. *Journal of Materials Chemistry* 14(19): 2889-2895.
- Mehta, B. and Singh, V. N. (2005). Structural, electrical and gas-sensing properties of In₂O₃ : Ag composite nanoparticle layers. *Pramana* 65(5): 949-958.
- Misra, S. C. K.; Mathur, P.; Yadav, M.; Tiwari, M.K.; Garg, S.C. and Tripathi, P. (2004). Preparation and characterization of vacuum deposited semiconducting nanocrystalline polymeric thin film sensors for detection of HCl. *Polymer* 45(25): 8623-8628.
- Mishra, R. and Rajanna, K. (2005). Metal-Oxide Thin Film with Pt, Au and Ag Nano-Particles for Gas Sensing Applications. *Sensors and Materials* 17(8): 433-440.
- Mehul N. Patel; Ryan D. Williams; R. Alan May; Hiroshi Uchida; Keith J. Stevenson and Keith P. Johnston, Electrophoretic Deposition of Au Nanocrystals inside Perpendicular Mesochannels of TiO₂. *Chem. Mater.*, 2008, 20 (19), pp 6029-6040
- ^aMusat, V.; Fortunato E.; Botelho do Rego, A.M. and Monteiro, R. (2008). Sol-gel cobalt oxide-silica nanocomposite thin films for gas sensing applications. *Thin Solid Films* 516(7): 1499-1502.
- ^bMusat, V.; Budrugaec, P.; and Gheorghies , C. (2008). Effect of reagents mixing on the thermal behavior of sol-gel precursors for silica-based nanocomposite thin films. *Journal of Thermal Analysis and Calorimetry*, 94(2): 373-377.
- Patel, M. N.; Uchida, H.; et al. (2007). Nanocrystal infusion in mesoporous metal oxide thin films. 2007 AIChE Annual Meeting, Salt Lake City, UT.
- Penza, M.; Rossi, R.; Alvisi, M.; Signore, M.A.; Cassano, G.; Dimaio, D.; Pentassuglia, R.; Piscopiello, E.; Serra, E. and Falconieri, M. (2009). Characterization of metal-modified and vertically-aligned carbon nanotube films for functionally enhanced gas sensor applications. *Thin Solid Films* 517(22): 6211-6216.
- Anna De Girolamo Del Mauro; Angelica Immacolata Grimaldi; Vera La Ferrara; Ettore Massera; Maria Lucia Miglietta; Tiziana Polichetti; and Girolamo Di Francia (2009). A simple optical model for the swelling evaluation in polymer nanocomposites. *Journal of Sensors* 2009, Volume 2009 (2009), Article ID 703206.
- Satyajit, S.; Ludwig, L.; Cho, H.J.; Duarte, J.; Seal, S. (2005). Effect of Air-Pressure on Room Temperature Hydrogen Sensing Characteristics of Nanocrystalline Doped Tin Oxide MEMS-Based Sensor. *Journal of Nanoscience and Nanotechnology*, 5(11): 1864-1874.

- Shen, Y.; Yamazaki, T.; Liu, Z.; Meng, D. and Kikut, T. (2009). Hydrogen sensing properties of Pd-doped SnO₂ sputtered films with columnar nanostructures. *Thin Solid Films*, 517(21): 6119-6123.
- Siriwong, C; (2009). Gas sensing properties of WO₃-doped ZnO nanoparticles synthesized by flame spray pyrolysis. *Proceedings of IEEE Sensors. IEEE Sensors 2009 Conference - SENSORS 2009*. (pp 118-123).
- Sun, T.; Donthu, S.; Sprung, M.; D'Aquila, K.; Jiang Z.; Srivastava, A.; Wang, J. and Dravid, V. P. (2009). Effect of Pd doping on the microstructure and gas-sensing performance of nanoporous SnO_x thin films, *Acta Materialia* 57(4): 1095-1104.
- Tai, H., Jiang, Y.; Xie, G.; Yu, J.; Chen, X. (2007). Fabrication and gas sensitivity of polyaniline-titanium dioxide nanocomposite thin film. *Sensors and Actuators, B: Chemical* 125(2): 644-650.
- Tai, H.; Jiang, Y.; Xie, G.; Yu, J.; Chen, X. and Ying, Z. (2008). Influence of polymerization temperature on NH₃ response of PANI/TiO₂ thin film gas sensor. *Sensors and Actuators, B: Chemical* 129(1): 319-326.
- Tang, H., Yan, M.; Zhang, H.; Li, S.; Ma, X.; Wang, M. and Yang, D. (2006). A selective NH₃ gas sensor based on Fe₂O₃--ZnO nanocomposites at room temperature. *Sensors and Actuators B* 114(2): 910-915.
- Tiwari, A. and Li, S. (2009). Vacuum-deposited poly(o-phenylenediamine)/WO₃.nH₂O Nanocomposite thin film for NO₂ gas sensor. *Polymer Journal* 41(9): 726-732.
- Tiwari, A.; Prabakaran, M.; Pandey, R. R. and Li, Songjun. (2010). Vacuum-deposited thin film of aniline-formaldehyde condensate/WO₃•nH₂O nanocomposite for NO₂ Gas sensor. *Journal of Inorganic and Organometallic Polymers and Materials* 20(2): 380-386.
- Wisitsoraat, A.; Tuantranont, A.; Thanachayanont, C.; and Singjai, P. (2006). Carbon nanotube-SnO₂ composite gas sensor prepared by electron beam evaporation. *Proceedings of 1st IEEE International Conference on Nano Micro Engineered and Molecular Systems*, pp 1487-1490, 2006. Article Number: 4135225, Zhuhai, China, January 18 - 21, 2006.
- ^aWisitsoraat, A.; Tuantranont, A.; Thanachayanont, C. and Singjai, P. (2007). Gas sensing properties of CNT-SnO₂ nanocomposite thin film prepared by e-beam evaporation. *Proceedings of IEEE Sensors. The 6th IEEE Conference on SENSORS, IEEE SENSORS 2007*. (pp 550-553), 2007. Article Number: 4388457.
- ^bWisitsoraat, A., Comini, E.; Sberveglieri, G.; Wlodarski, W. and Songsiriritthigul P. (2007). Studies of TiO₂ based mixed oxide thin film materials prepared by ion-assisted electron beam evaporation for gas sensing applications. *Materials Research Society Symposium Proceedings - Functional Materials for Chemical and Biochemical Sensors*. vol 1010 (pp 34-41), 2007.
- Xin, L.; Liu, J.; Zhu, C. (2005). The study of adsorption gas sensor based carbon nanotube film. *Science in China. Series E: Engineering & Materials Science* 48(4): 372-384.
- Yan, X.; Xie, G.; Du, X.; Tai, H.; Jiang, Y. Preparation and characterization of polyaniline/indium(III) oxide (PANI/In₂O₃) nanocomposite thin film. *Proceedings of SPIE - The International Society for Optical Engineering*. 4th International

Symposium on Advanced Optical Manufacturing and Testing Technologies: Advanced Optical Manufacturing Technologies. vol 72822009. Article Number: 72823C.

- Yang, D.; Chen, B.; Nikumb, S.; Chang, C.; Lin, C. (2008). Surface plasmon resonance gas sensors using Au-WO_{3-x} nanocomposite films. *Proceedings - 2nd Int. Conf. Sensor Technol. Appl.*, SENSORCOMM 2008, August 25-31, 2008 - Cap Esterel, France.
- Yang, M. J.; Li, Y.; She, Y.; Ling, M. F.; Wang, H. P. (2002). Humidity Sensors using In-situ Synthesized Sodium Polystyrenesulfonate/ZnO nanocomposites. *Proceedings of IEEE Sensors*, Orlando, FL.



Advances in Nanocomposites - Synthesis, Characterization and Industrial Applications

Edited by Dr. Boreddy Reddy

ISBN 978-953-307-165-7

Hard cover, 966 pages

Publisher InTech

Published online 19, April, 2011

Published in print edition April, 2011

Advances in Nanocomposites - Synthesis, Characterization and Industrial Applications was conceived as a comprehensive reference volume on various aspects of functional nanocomposites for engineering technologies. The term functional nanocomposites signifies a wide area of polymer/material science and engineering, involving the design, synthesis and study of nanocomposites of increasing structural sophistication and complexity useful for a wide range of chemical, physicochemical and biological/biomedical processes. "Emerging technologies" are also broadly understood to include new technological developments, beginning at the forefront of conventional industrial practices and extending into anticipated and speculative industries of the future. The scope of the present book on nanocomposites and applications extends far beyond emerging technologies. This book presents 40 chapters organized in four parts systematically providing a wealth of new ideas in design, synthesis and study of sophisticated nanocomposite structures.

How to reference

In order to correctly reference this scholarly work, feel free to copy and paste the following:

Dongfang Yang (2011). Nanocomposite Films for Gas Sensing, Advances in Nanocomposites - Synthesis, Characterization and Industrial Applications, Dr. Boreddy Reddy (Ed.), ISBN: 978-953-307-165-7, InTech, Available from: <http://www.intechopen.com/books/advances-in-nanocomposites-synthesis-characterization-and-industrial-applications/nanocomposite-films-for-gas-sensing>

INTECH
open science | open minds

InTech Europe

University Campus STeP Ri
Slavka Krautzeka 83/A
51000 Rijeka, Croatia
Phone: +385 (51) 770 447
Fax: +385 (51) 686 166
www.intechopen.com

InTech China

Unit 405, Office Block, Hotel Equatorial Shanghai
No.65, Yan An Road (West), Shanghai, 200040, China
中国上海市延安西路65号上海国际贵都大饭店办公楼405单元
Phone: +86-21-62489820
Fax: +86-21-62489821

© 2011 The Author(s). Licensee IntechOpen. This chapter is distributed under the terms of the [Creative Commons Attribution-NonCommercial-ShareAlike-3.0 License](https://creativecommons.org/licenses/by-nc-sa/3.0/), which permits use, distribution and reproduction for non-commercial purposes, provided the original is properly cited and derivative works building on this content are distributed under the same license.

IntechOpen

IntechOpen