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Nanostructured WO_3 gas sensors

Theses

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1. Introduction and objectives

Continuous monitoring of air quality and the concentration of pollutants is an important factor and a great challenge for researchers. In the past decades the industrial and mobility development raised serious environmental and health safety issues. The reduction of environmental pollution, toxic compounds and explosive gases is essential, thereby, during industrial production, product development and environmental control the continuous monitoring and the accurate measurement of critical pollutant concentration are indispensable.

Gas sensors detect some of the physical parameters or phenomena caused by the chemical reaction of the measurable gas. The detection is converted into an electronic signal and interpreted by direct quantification or via computer connection. Sensors developed in recent decades are able to detect almost every kind of dangerous and flammable gases; however the complexity of their operation leads to high production costs and also to high power consumption in most cases. The inherent advantage of solid state sensors is their fabrication by semiconductor technologies, therefore small-sized, energy-efficient, portable sensor systems can be produced in large quantities. By widespread application of these sensors personal protection equipment and large-scale monitoring networks can be prepared. Implemented in appropriate communication systems (IoT, Internet of Things) sensors can provide faster and more accurate picture of the environmental status than ever. The huge potential of microsensors is well demonstrated by the Japanese example from the 60's[1] when the thin film SnO_2-based carbon-hydrogen detectors were introduced in retail market led to dramatic reduction in the number of residental fire and explosion accidents.

In my thesis I present the development of sensor fabrication technologies to form nanostructured WO_3, a gas sensing semiconductor metal-oxide that utilizes conductivity transduction principle. The thesis also includes a detailed description of the gas sensing properties of the developed sensors tested primarily for NH_3 and H_2S gases in the ppb-ppm concentration range.

The vast majority of gas sensors – especially retail devices[2] – are fabricated on alumina substrate and approximately 1 W power is necessary for heating their sensing layer to reach the optimum operating temperature. This level of energy consumption is too high for portable systems powered by battery[3]. The easiest way to achieve lower energy consumption is the reduction of the sensing area and the improvement of its heat insula-

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tion. The latter is not only important for total optimal energy consumption but also for integration of the electrical signal processor and different sensors on the same chip[4]. Different mathematical models can improve the selectivity and accuracy of sensing and/or classification of gas mixtures using a multi-element system[5]. Therefore the energy-efficient, high temperature micro-hotplate is an important component of the sensor. During my work I used micro-hotplates that had been developed in the MFA MEMS laboratory and improved for optimum thermomechanical properties by Ferenc Bíró[6]. My job was to integrate the unique preparation steps of different nanostructured WO_3 sensing layers into the fabrication sequence.

Tungsten-oxide is an n-type semiconductor with 2.6-3.6 eV band gap energy[7] and used not only in catalytic/photocatalytic and electrochromic applications, but also as the active layer of solid state gas sensors. Among others WO_3 is a widely examined material, because its many different morphologies and structures are potential candidates for gas sensing.

By the rapid development of nanotechnology processes, materials with well-controllable nanostructures can be prepared (e.g. WO_3), which opened new opportunities in sensor research. In the preparation of semiconductor metal-oxide solid state gas sensors the elaboration of appropriate metal-oxide structures and their processing compatibility with mass fabrication technologies of Si microtechnology is equally important.

The main motivation of my doctoral work was to develop WO_3-based gas sensors that – due to their new nanostructures – are able to detect certain gases in a quick, stabile and selective manner. In order to achieve these properties I prepared nanostructured WO_3-based systems and thin layers by alternative technologies and compared their gas sensing characteristics. I doped the WO_3 structures with gold and platinum particles by different technologies to investigate the effect of sensitization. The preparation of nanostructured WO_3 layers were performed by wet-chemical processes, taking into consideration the future implementation possibilities of the preparation steps into mass fabrication technology. Therefore, significant part of my research was the design and application of the entire sensor preparation technology.

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2. Experimental methods

The hexagonal WO_3 samples of different morphologies were synthetized by wet-chemical processes. Pure WO_3 nanocrystals, which can be prepared by acid-catalyzed hydrolysis at room temperature have monoclinic crystal structure [8], however combined with certain „contaminants" nanoparticles of other crystal structures can be formed. The Na^+ content of all precursors ($Na_2WO_4*2H_2O$) used during the synthesis facilitates the development of stabile, hexagonal crystal-structured WO_3 nanocrystals. Apart from the precursors, the presence of other salts also contributes to the development of different morphologies. Certain additives and cleaning steps also affect the evolving morphologies. Investigating several materials I treated all samples in a sealed autoclave at 120-180 °C. As a result of the optimal nucleation process I synthetized hexagonal crystal-structured WO_3 nanorods, nanonets and nanocarnations.

The chip size reduction can be achieved by proper adaptation of some special micro-electromechanical (MEMS) processes to the standard CMOS technology. With MEMS technologies sensors can be fabricated cost efficiently in minimum size and large quantity. The technique includes the masking, doping, etching and layer-depositing processes and can be supplemented with other unique steps. The membrane-structure is prepared by back side silicon bulk etching method and of course by appropriate layer-depositing and etching techniques. The operation of the Taguchi-type gas sensors needs elevated temperature to facilitate the ad- and chemisorption of gases (oxygen, water) which lead to the conductivity change of the sensing layer. The energy consumption of the device can be reduced by decreasing its size and by using appropriate thermal insulation. Therefore the sensors consist of a heated membrane that supports the sensing layer and an interdigital electrode for read-out. Most of the micro-hotplates operate steadily at elevated temperature (150-600 °C). Our micro-hotplate can achieve 400-500 °C with 20 mW power dissipation. During my work I deposited WO_3 samples of different morphologies by suspension dropping method onto the middle of the micro-hotplates. Having been dried the samples were tested for NH_3 gas in 10-100 ppm concentration range.

WO_3 nanorods with 70 nm diameter showed the most advantageous characteristics. To increase the sensitivity and enhance selectivity the sensing layer can be activated with certain other metals (or semi-metals)[9]. The most effective way is the sensitization with catalytic noble metals[10]. In my work I prepared platinum and gold nanoparticles and added them to the suspension of the WO_3 nanorod samples. The noble metal sensitized sensors were tested for ammonia and hydrogen-sulfide gas in the ppb-ppm concentration range.

Another main objective of my work was to develop a sensor layer-fabrication technology that can be easily integrated into the wafer-scale MEMS process. Taking these requirements into consideration I also prepared porous WO_3 thin layers in two ways (sol-gel and electrochemical etching) and optimized the processes such as to achieve the highest possible pore volume, while preserving the chemical and physical stability of the layer.

By sol-gel process well-controllable thin layers can be synthetized. Mesoporous WO_3 thin films were deposited on oxidized silicon substrate using different tenzide concentrations. The objective of these experiments was to prepare layers with the highest possible pore volume meanwhile sustaining the compact and uniform layer. The used non-ionic Pluronic F127 tenzide forms sphere micelles in the layer. After a heat treatment the finalized porous structure is created by the holes left behind by these sphere micelles. The prepared sols were selectively deposited on the micro-hotplate surface by

spin-coating combined with lift-off technique to achieve optimal layer thickness. In order to implement this process into fabrication technology I had to make minor modifications of the basic sensor structure.

Another widely applied method for controlled preparation of porous metal-oxide layer is the electrochemical dissolution process - also known as anodization. The structure of the metal-oxides produced this way is controllable within certain limits. On one hand it depends on the electronic characteristics of the initial metal (wolfram in my case), its contaminants and orientation, on the other hand also depends on the applied experimental parameters during the anodization; such as composition and concentration of the electrolyte, the temperature and the applied current density. In order to achieve optimum parameters I used 0.3 M oxalic acid – that is described in the literature as showing the best etching properties[11] – at room temperature and investigated the effect of current density. During the experiments I let the process run at constant voltage until the current reached the range of mA. The complete lateral etching and oxidization of the wolfram metal are preconditions of the sensor functionality, preferably forming a pore system perpendicular to the metal surface. I integrated this process into the chip production technology by developing a laterally selective etching method, however I had to apply minor modifications of the basic sensor structure.

The mesoporous WO_3 thin layers prepared in these two ways were also sensitized by noble metals, which initiate changes either inside the structure or on the surface of the layer and could lead to increased gas sensitivity.

In the first method, I doped the surface of the WO_3 sensor layer with noble metal (for porous WO_3, the inside surface of the pores), so it can achieve higher gas sensitivity. The quality of the noble metal could affect the gas selectivity. The noble metal nanoparticles deposited on the layer surface by dropping were usually separated; however in some case they formed smaller aggregates.

The mesoporous WO_3 thin layers prepared by sol-gel or electrochemically etching technique were also sensitized with ALD Pt-layer in order to compare the effect of metal deposition techniques on gas sensor sensitivity. As the Pt-layer was to deposit inside the pores, precursor pulses and intermediate purging phases had to be extended, allowing the products to diffuse into the pores, and let the unreacted precursors and by-products to leave the surface. These modifications enhance the activation by covering the entire surface of the porous WO_3 thin layers.

3. Results

3.1 Preparation and comparison of different WO_3 nanocrystals

In the first part of my work, I prepared WO_3 samples with hexagonal crystal structure and different nano-morphologies. The additives and the purification processes used in the preparation play an important role in the formation of appropriate crystal structure and morphology. The tungsten-oxide samples prepared by hydrothermal process using Na_2SO_4 formed bundles of 50 to 70 nm diameter nanorods that can be separated by ultrasonic treatment. All the WO_3 layers were droplet deposited in suspended form to the micro-hotplate and dried. Sensors were tested with 10-100 ppm ammonia gas. I concluded that both the morphology of the samples and the "impurities" have high influence on the gas sensitivity. The 50-70 nm diameter nanorod structured WO_3 showed excellent gas detection properties. This sensor exhibited fast response and regeneration time with a stabile signal to NH_3 concentration below 100 ppm *(Figure1.)*. Comparing the bundled and separated nanorod structures the separated sample presented 5-times higher gas sensitivity due to the comparability of the diameter and the space charge layer thickness.

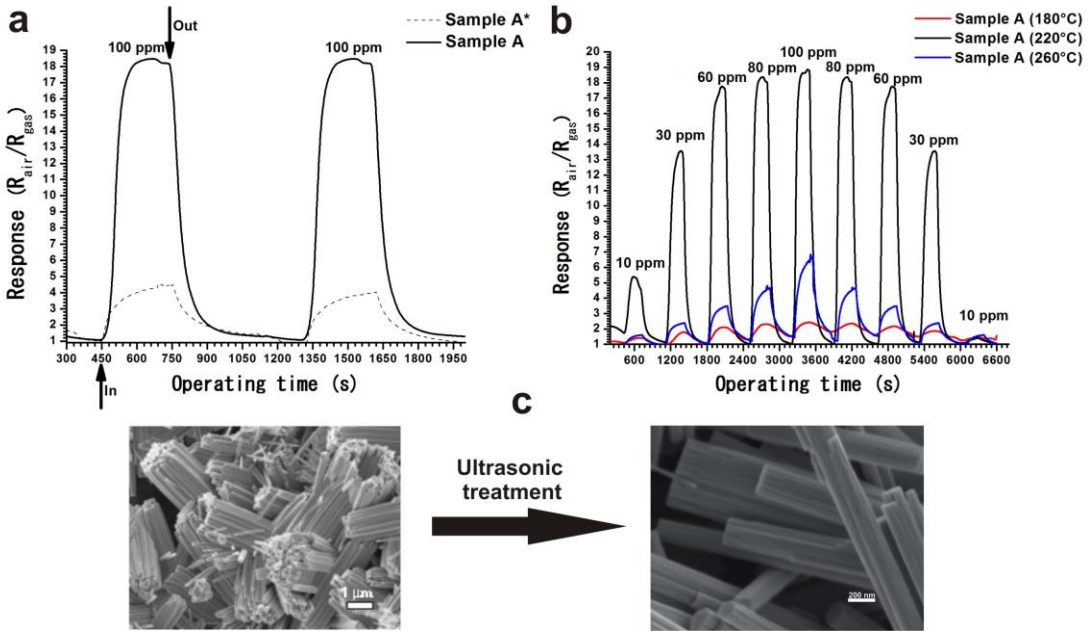

Figure 1. *(a) Response of Na_2SO_4 catalyzed WO_3 layers with and without ultrasonic treatment for 100 ppm NH_3, and (b) response of ultrasonic treated WO_3 layers tested for different temperatures. (c) SEM views of the two different WO_3 samples.*

3.2 Metal activated nanocrystals and their gas selectivity

In order to increase the gas selectivity and sensitivity, WO_3 nanorod samples were sensitized with gold and platinum nanoparticles. I tested the prepared gas sensors with ammonia and hydrogen-sulfide gases and found that the gold nanoparticles significantly increased the H_2S sensitivity and selectivity (5-times higher sensitivity compared to the non-doped sample). The sensors also reliably measure hydrogen-sulfide in the low (ppb) concentration range. The signal of the sensors can be characterized by 30-60 s response time and slow (300 s) regeneration time. During the regeneration of the sensor two separate processes can be distinguished: rapid regeneration (oxygen chemisorption) on bare WO_3 and slow sulphur desorption in the vicinity of gold particles (*Figure 2.*).

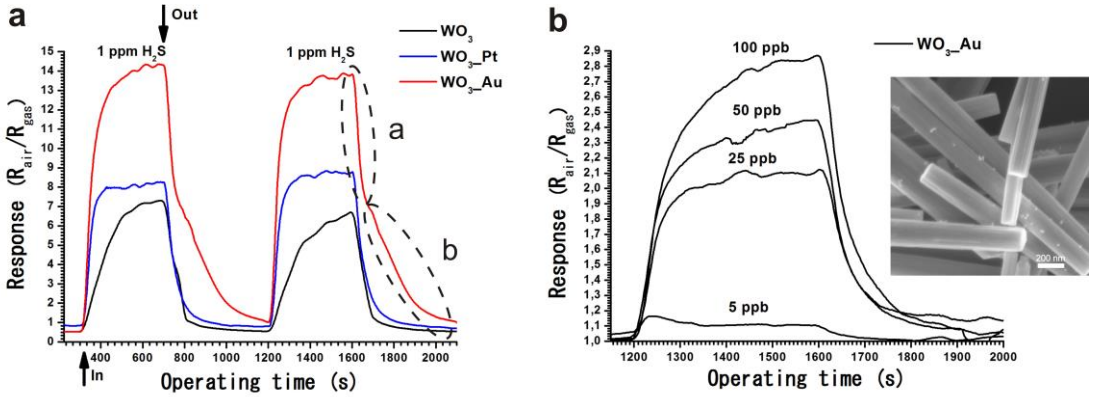

Figure 2. *Signal shape of pure and metal-activated hexagonal WO_3 nanorod layers for 1 ppm H_2S gas concentration at 260 °C. (b) SEM image and signal shape of the gold nanoparticles activated WO_3 layers for H_2S gas below 1 ppm at 260 °C.*

3.3 Mesoporous WO_3 layers

As the drop coating technique used to deliver the sensing WO_3 onto the micro-hotplate surface did not provide reproducible layers, the second part of the dissertation focuses on wafer-scale, microtechnology compatible techniques for preparation of mesoporous WO_3 thin films on the surface of micro-hotplates. Pluronic F127 surfactant was used to increase the pore volume of thin films prepared by sol-gel technique. Using a 0.8 mM surfactant and 300 °C heat treatment I achieved a compact mesoporous layer of characteristic 5 to 20 nm pore diameter (*Figure 3.*).

Additionally, I prepared porous WO_3 layer by electrochemical etching of deposited wolfram metal layer. The completely etched layer has perpendicular pores to the surface.

The process parameters of the two porous structures were optimized to achieve the maximum pore volume while maintaining the compact, contiguous layer with uniform properties. For better functional comparability, I set the film thickness of both WO_3 layers at 200 nm.

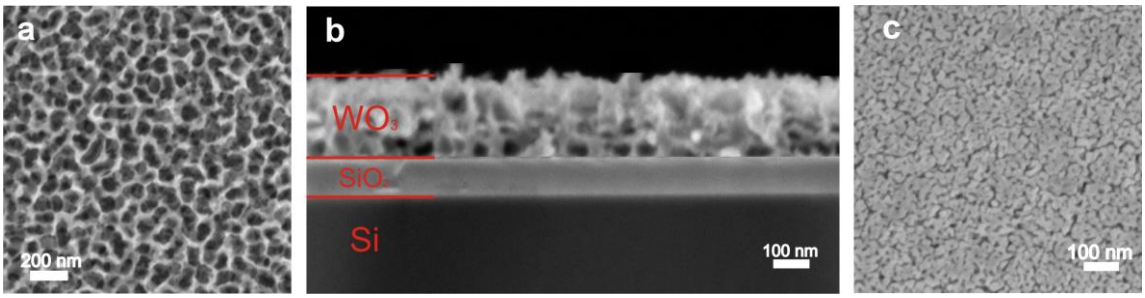

Figure 3. *(a) SEM image of the electrochemically formed (55 V) and heat treated WO_3 thin layer at 400 °C. (b) Sectional SEM image of WO_3 layer (~250 nm) anodized from 200 nm wolfram metal on 55 V constant voltage. (c) SEM image of the WO_3 thin layer prepared with sol-gel method.*

3.4 Noble metal doped mesoporous WO_3 thin layers

I activated the surface of the WO_3 sensing layer with noble metal (in case of porous WO_3, the inside of the pores) in order to achieve higher gas sensitivity. The material quality of the noble metal influenced the gas selectivity. The metal nanoparticles applied by the dropping technique are separate, or they may form smaller aggregates on the surface of the layer. Calculating with a drop of 150 μm diameter mesoporous WO_3 and 1 nM nanoparticle concentration, approximately 50 to 70 individual noble metal nanoparticles appear on the lateral surface of 1 μm^2 WO_3.

The mesoporous WO_3 thin films were sensitized with atomic layer deposited (ALD) platinum and also with drop delivered noble metal nanoparticles. Applying extended pulses and purgetime the surface of the mesoporous layers can be uniformly coated with ALD platinum along the 200 nm depth of pores. However, instead of contiguous layers, evenly distributed, well-separated Pt particles of 2-5 nm diameters were found over the surface (*Figure 4.*).

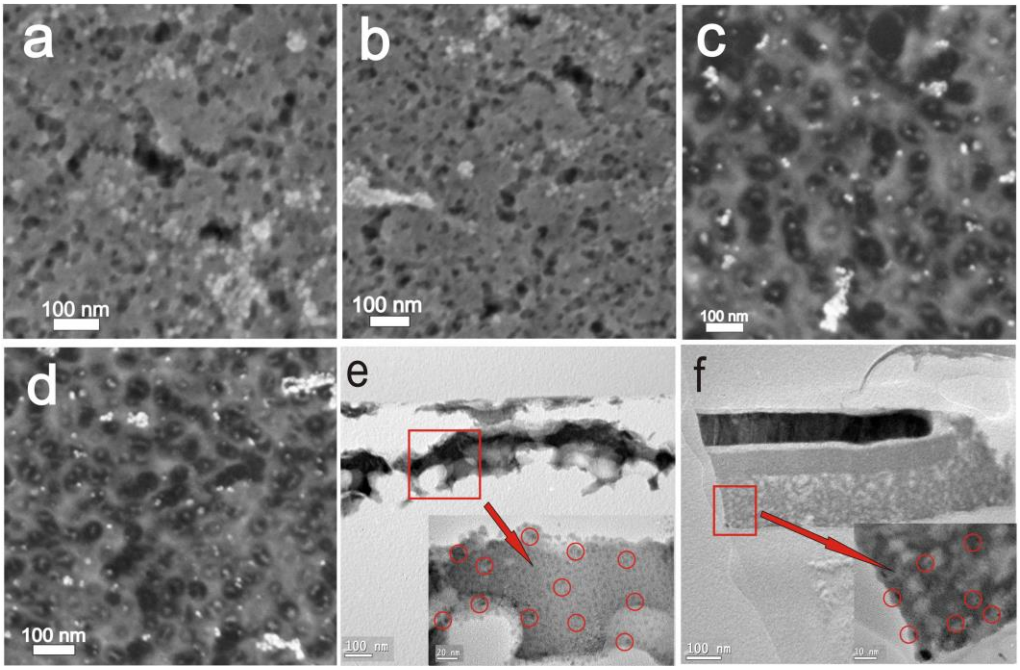

Figure 4. *Droplet-deposited gold (a) and platinum (b) nanoparticles on sol-gel formed mesoporous WO_3 layers (SEM views), Anodized WO_3 layers sensitized with gold (c) and platinum (d) nanoparticles (SEM views) Anodized (e) and sol-gel formed (f) WO_3 layer sensitized with ALD Pt (TEM views).*

3.5 Mesoporous WO_3 sensing layers

The advantage of thin films over the piles of nanorods is that they have stabile and reproducible structure, but typically exhibit less sensitivity. In my experiments, I examined the sensitivity and signal characteristics for NH_3 and H_2S gases of all layers (non-doped, platinum and gold nanoparticle sensitized and the ALD platinum doped). The responses of the electrochemically formed and sol-gel WO_3 layers clearly show that the noble metal doped samples exhibit higher sensitivity at all temperatures and at all gas concentrations than non-doped WO_3 references when exposed to hydrogen-sulfide gas. For H_2S gas the layers doped with ALD platinum have significantly increased sensitivity by more than one order of magnitude, and on the other hand, the responses of the sample doped with gold nanoparticles are higher than the layer doped with platinum nanoparticles. The analyzed parameters of the gas sensors are therefore strongly depend on the nanostructure of the WO_3 layer and the operating temperature. For H_2S, stabile, reproducible signal characteristics were obtained at ~ 220 °C, and for NH_3 at ~ 260 °C (*Figure 5.*). The electrochemically formed WO_3 sensor showed quick response and regeneration time acceptable in practice (t_{90}<45 s). Another difference in signal characteristic is that the noble metal activated sensors are much more sensitive for H_2S than for NH_3. Typical response signal is 5-7 times higher for H_2S, which offers selective sensing of hydrogen sulfide. Selective gas detection can be achieved by operating the two types at different temperatures. The phenomena of sensitivity and selectivity were also explained and verified by calculating the activation energies of adsorption mechanism.

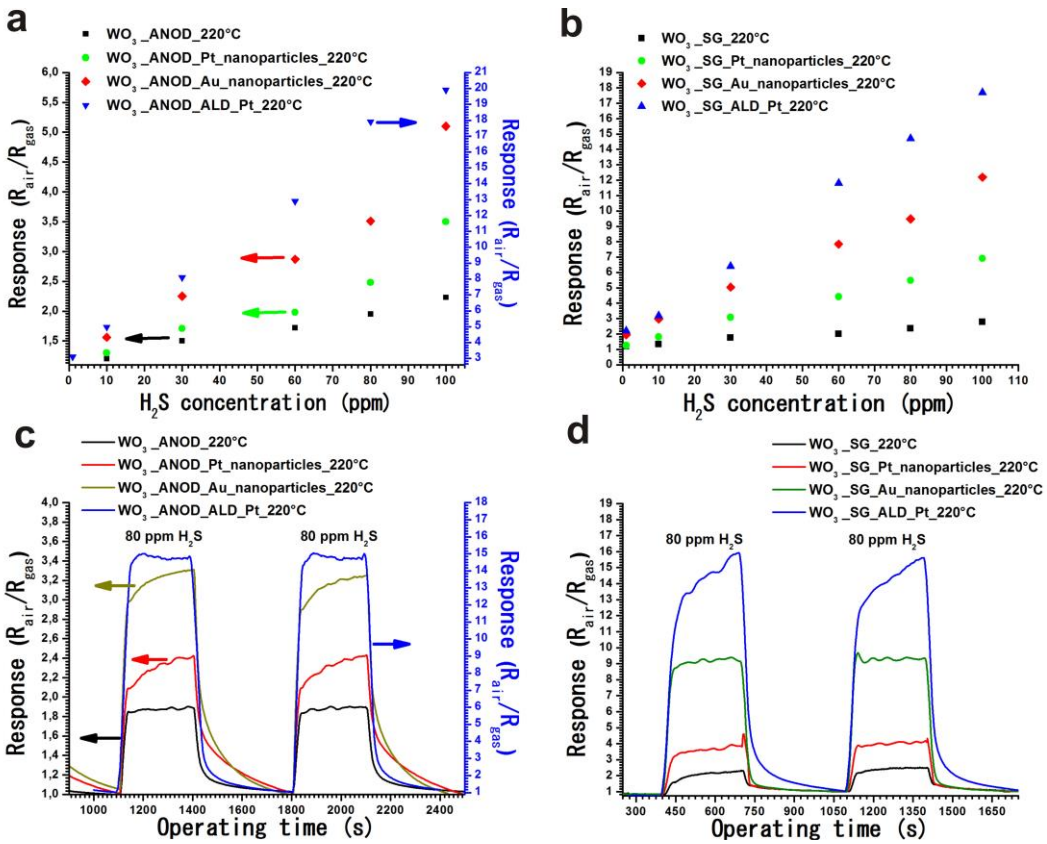

Figure 5. *Responses of electrochemically formed (a) and sol-gel deposited (b) layers for H_2S exposure. Transients of electrochemically (c) and sol-gel (d) formed sensors for pulse-type exposure of 80 ppm H_2S.*

3.6 Comparison of WO_3 nanorod based and electrochemically prepared sensors in H_2S gas measurement

Gold nanoparticles activated WO_3 nanorods and ALD platinum sensitized porous WO_3 thin films synthesized by anodization method showed the highest sensitivity and selectivity (stabile and quick response) for H_2S gas. The gold nanoparticles sensitized WO_3 nanorods-based sensor exhibits 9-times higher sensitivity at optimum operating temperature than the ALD platinum coated porous (anodized) WO_3 thin-film. The difference can be explained by the higher sensitizing effect of gold particles and the structural difference of WO_3 layers. The gold metal activated WO_3 nanorods (~30 s) and ALD platinum coated mesoporous WO_3 thin layer (~45 s) sensors have small difference between the response time for hydrogen-sulfide (t_{90}), however the differences between their regeneration time and signal characteristics are much more significant. While the signal of anodized, Pt coated WO_3 sensor has "fast" desorption kinetics (~100 s), signal of the gold-doped WO_3 nanorods sample consists of two different reactions, and therefore has much longer regeneration time (~300 s) (*Figure 6.*).

A sensor can be applied in practice if the responses are reproducible and stable during long-term testing. The sensitivity of 3-3 pieces of the two structures was investigated for a 1 week-long continuous measurement for cyclic exposure to 10 ppm H_2S gas (stability test). None of the samples' sensitivity reduced during the measurement. The small variation of the signal response may be attributed to the fluctuation of the baseline. The difference in the stability test is that while the wafer-scale technology prepared, ALD platinum coated porous WO_3 samples had minor variance of sensitivity (<1 %), the gold nanoparticle activated WO_3 samples were prepared by dropping had higher variance of sensitivity (8 %) (*Figure 6.*).

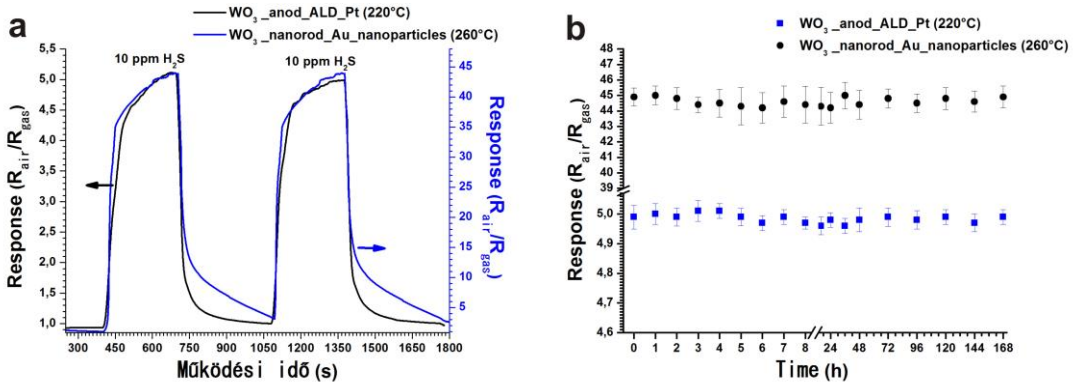

Figure 6. *Sensor signals (a) and stability test (b) of gold nanoparticle activated WO_3 nanorods and ALD platinum sensitized porous WO_3 thin-films synthesized by anodization method for 10 ppm H_2S gas.*

4. List of theses

1. I synthetized hexagonal crystal-structured WO_3 nanocrystal suspension of different morphologies by hydrothermal method in presence of Na_2SO_4, K_2SO_4, NaCl, and first using $ZnSO_4$ additives. Gas sensing properties of the WO_3 layers drop deposited on the surface of micro-hotplates were compared with layers formed by sol-gel process, anodization and reactive deposition methods [1][2].

2. I have experimentally determined how the characteristic geometric dimensions influence the sensitivity of the nanostructured WO_3 gas sensors. Bundles of 50-70 nm diameter nanorods were formed by hydrothermal process and Na_2SO_4 additive layers, which can be separated by ultrasonic treatment. Comparing the two structures of different diameters, I found that the sensor with smaller rod diameter exhibits 5-times higher sensitivity due to the comparability of the diameter and space charge layer thickness. The phenomenon is similar to the known effect for thin films, however in my case the dimensional effect is much more intense [2].

3. Investigating gold and platinum nanoparticles sensitized WO_3 nanorods I have determined that gold-doped sensors can selectively detect H_2S over 25 ppb. These sensors are characterized by 30 to 60 s response and slow (300 s) regeneration times. During the regeneration of the sensor two separate processes can be distinguished: rapid regeneration (oxygen chemisorption) on bare WO_3 and slow sulphur desorption in the vicinity of gold particles [3][4].

4. I have developed wafer-scale, laterally selective mesoporous WO_3 thin film processes to cover the micro-hotplate surface by sol-gel method or electrochemical etching of a W layer. For the MEMS compatible layer preparation by sol-gel method (lift-off, photolithography, etc.) I have used for the first time Pluronic F127 tenzide for pore volume extension. I have experimentally determined that compact mesoporous layer with 5-20 nm pore diameter can be achieved by heat treatment at 300 °C with 0.014 : 0.0046 : 1 (WCl_6 : F127 : ethanol) mol ratio and 0.8 mM tenzide concentration. At higher temperatures the layer becomes fragmented, whereas higher tenzide concentrations is not suitable for layer formation [5][6].

5. For the first time, I integrated the electrochemical process in the sensor fabrication technology to selectively form porous WO_3 layer on the top of micro-hotplates. By electrochemical etching with 0.3 M oxalic acid and constant voltage (55 V) I prepared WO_3 layer with pores of 50-70 nm diameter and perpendicular to the surface. I experimentally determined the required processing parameters for the completely etched 220 – 250 nm thick porous WO_3 film (200 nm wolfram layer and approximately 20 minutes of etching) [6].
6. For the first time I used atomic layer deposition technique for sensitizing the nanostructured sensing layer of a conductivity-type gas sensor. By the extension of pulses (0.4 and 4 s) and purge (15 s) time the surface of the sol-gel or electrochemically formed mesoporous layers can be uniformly coated with Pt along the pore depth of 200 nm. I found that during the nucleation period of layer growth the nominally 8 nm thick Pt does not form contiguous layer, but composed of 2–5 nm diameter metal particles evenly distributed over the surface. [6].
7. I concluded that the sensitivity and dynamics of gas sensors are significantly depend on the nanostructure of the WO_3 layer and also on the operating temperature. For H_2S stabile, reproducible signal characteristics were obtained at ~ 220 °C, whereas for NH_3 ~ 260 °C proved the best. The electrochemically formed WO_3 sensor showed quick response and regeneration time making them realistic in practice (t_{90}<45 s). Selective gas detection can be achieved by operating the two types of sensors at different temperatures. The phenomena of sensitivity and selectivity were also explained and verified by calculating the activation energies of adsorption mechanisms [6].

5. List of publications

5.1 Publications directly related to the PhD dissertation:

[1] M. Takács, Cs. Dücső, Z. Lábadi and A. E. Pap, Effect of hexagonal WO_3 morphology on NH_3 sensing, *Procedia Engineering* 87 (**2014**) 1011–1014

[2] M. Takács, Cs. Dücső, A. E. Pap, Fine-tuning of gas sensitivity by modification of nano-crystalline WO_3 layer morphology, *Sensors and Actuators B* 221 (**2015**) 281–289, **IF:4,758**

[3] M. Takács, D. Zámbó, A. Deák, A.E. Pap, I. Bársony, Gas sensitivity enhancement of WO_3 nano-rods by gold nanoparticles, *Procedia Engineering* 120 (**2015**) 1128–1131

[4] M. Takács, D. Zámbó, A. Deák, A. E. Pap, Cs. Ducső, WO_3 nano-rods sensitized with noble metal nano-particles for H_2S sensing in the ppb range, *Materials Research Bulletin* 84 (**2016**) 480-485, **IF: 2,435**

[5] M. Takács and A. E. Pap, Gas sensitivity of sol-gel prepared mesoporous WO_3 thin film, *Procedia Engineering,* 168 (**2016**) 289–292

[6] M. Takács, Cs. Dücső and A. E. Pap, Nano-structured WO_3 layers sensitized with ALD Pt for quick detection of H_2S, *Journal of Materials Science: Materials in Electronics* 28 (**2017**) 17148-17155, **IF: 2,019**

5.2 Publications indirectly related to the PhD dissertation:

[7] F. Bíró, Gy. Z. Radnóczi, Zs. Baji, M. Takács, I. Bársony, Pt deposition techniques for catalytic activation of nano-structured materials, *Procedia Engineering* 168 (2016) 1148-1151

[8] F. Bíró, Cs. Dücső, Gy. Z. Radnóczi, Zs. Baji, M. Takács, I. Bársony, ALD nano-catalyst for micro-calorimetric detection of hydrocarbons, *Sensors and Actuators B* 247 (**2017**) 617-625, **IF: 5,401**

[9] S. I. Boyadjiev, O. Kéri, P. Bárdos, T. Firkala, F. Gáber, Zs. K. Nagy, Zs. Baji, M. Takács, and I. M. Szilágyi, TiO_2/ZnO and ZnO/TiO_2 core/shell nanofibers prepared by electrospinning and atomic layer deposition for photocatalysis and gas sensing, *Applied Surface Sciences* 424 (2) (**2017**) 190-197, **IF: 3,387**

5.3 Presentations:

[1] M. Takács, Cs. Dücső, Z. Lábadi and A. E. Pap, Effect of hexagonal WO_3 morphology on NH_3 sensing, Conference of EUROSENSORS, Brescia, Italy (**2014**) poster

[2] M. Takács, D. Zámbó, A. Deák, A. E. Pap, I. Bársony, Gas sensitivity enhancement of WO_3 nano-rods by gold nanoparticles, Conference of EUROSENSORS, Freiburg, Germany (**2015**) poster

[3] Takács Máté, Dücső Csaba, Pap Andrea Edit, Nanoszerkezetű WO_3 vékonyfilmek előállítása gázérzékelők mikrostruktúrák részére, Innováció a természettudományban 2015- Doktorandusz Konferencia, Szeged, (**2015**) oral presentation

[4] M. Takács and A. E. Pap, Gas sensitivity of sol-gel prepared mesoporous WO_3 thin film, Conference of EUROSENSORS, Budapest, Hungary (**2016**) poster

[5] Takács Máté, Pap Andrea Edit, Nanoszerkezetű WO_3 vékonyrétegek előállítása és alkalmazása gázérzékelő mikrostruktúrákban, Oláh György Doktori Iskola XIV. Konferenciája, Budapest, (**2017**) oral presentation

[6] Volentiru Emőke, Kerekes Nóra, Takács Máté, Hórvölgyi Zoltán, Pórusos SnO_2 és TiO_2 bevonatok előállítása szol-gél technikával, Proceeding of the "Műszaki Kémiai Napok 2014" Conference of Chemical Engineering, Veszprém, Hungary, (**2011**) oral presentation

[7] M. Takács, J. Kawakita, T. Chikiyow, Detection of dew condensation by micro galvanic-coupled arrays, SFJ meeting conference, Kanazawa, Japan, (**2017**) oral presentation