

# Room-temperature sensitivity to NO<sub>2</sub> exposure of electrochemically-deposited nanostructured ZnO layers

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**Abstract.** This paper reports studies on the sensitivity of ZnO layers to NO<sub>2</sub> exposure. ZnO layers were fabricated by electrochemical deposition on the surface of a quartz crystal microbalance (QCM) with Au electrodes. The sensitivity was estimated using the frequency-time characteristics of the QCM. For this purpose, the resonance frequency shift was measured. The sorption process was investigated in a NO<sub>2</sub> gas flow. The change in the resonance frequency,  $f$ , of the QCM as a function of the loaded mass of NO<sub>2</sub> was followed for a NO<sub>2</sub> concentration of 500 ppm. Under gas exposure, the frequency decreased and reached saturation in five min. A frequency shift of 38 Hz was measured and a mass loading of 8.39 ng was calculated. The resonance frequency showed a very good recovery within two minutes after the NO<sub>2</sub> flow was switched off. The results demonstrate that the electrodeposited nanostructured ZnO layers have a potential for application as NO<sub>2</sub> gas sensors.

## 1. Introduction

Recently, TCO materials, and especially ZnO, have shown a growing potential for applications in the development of new optoelectronic and electronic devices. Having a high chemical stability, a low dielectric constant and a high optical transmittance, ZnO has found numerous uses as dielectric ceramics, pigment, catalyst, transparent conductive electrode and sensing material in solar cells, gas sensors, etc. [1- 4]. In particular, an increase in the gas sensitivity and selectivity for different gases has been reported by doping ZnO films with different elements [3-5].

In this work, the sensitivity of undoped thin films of ZnO to exposure to NO<sub>2</sub> was estimated by means of the quartz crystal microbalance (QCM) method.

## 2. Experimental

Thin ZnO nanostructured films were deposited by an electrochemical process from a slightly acidic aqueous solution of ZnCl<sub>2</sub> ( $5 \times 10^{-3}$  M) and KCl (0.5 M) with pH 4.0 at 80 °C and –1000 mV (vs. SCE) using a three-electrode electrochemical cell [6]. The electrolyte was agitated by magnetic stirrer. The quartz crystal resonator with a Au electrode was used as a cathode. A spectrally-pure graphite plate

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electrode was used as an anode. The deposition was carried out for between 30 and 60 minutes while controlling the redox potential of the system. In addition, the total oxygen content in the solution was controlled by a DO&T meter (Hanna Instruments 9146). The thickness of the ZnO films thus prepared was in the range 0.2  $\mu\text{m}$  – 0.5  $\mu\text{m}$ .

Quartz crystal resonators were used as microbalances to monitor the speed of electrodeposition of the ZnO nano-layers. The oscillators consisted of thermo-stable polished AT-cut quartz plates with a diameter of 8 mm with gold electrodes with a thickness of 600 nm and a surface area of 0,1256  $\text{cm}^2$  in an HC-49 type package. A 16-MHz base resonance frequency was thus obtained.

The gas sensitivity of the electrochemically-deposited ZnO on QCM was studied by exposure to  $\text{NO}_2$ . The resulting structure was kept in air until saturation in the frequency value was reached. The temperature in the test chamber was kept constant ( $25^\circ\text{C} \pm 0.5^\circ\text{C}$ ) by a thermostat. The concentration of the  $\text{NO}_2$  gas flowing into the thermally-stabilized measurement chamber was 500 ppm. The resonance frequency was measured by a frequency counter and recorded on a PC. The experimental setup for measuring the sensing properties of the ZnO-QCM system was described in detail in [7]. The frequency accuracy was  $\sim 0.1$  Hz.

### 3. Results and discussion

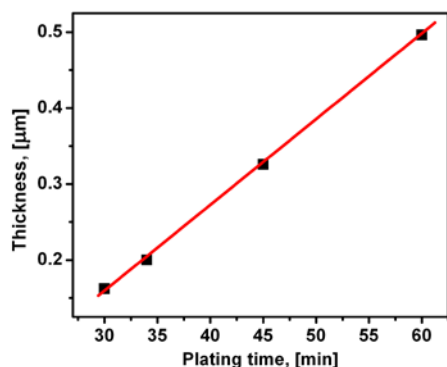
To determine the films' growth rate, several experiments were performed involving deposition of ZnO on a quartz resonator surface, the ZnO layers being deposited for four different time durations – 30, 35, 45 and 60 min. Figure 1 shows the dependence of the ZnO films' thickness on the deposition time. The layers' thickness was calculated from the change in the resonance frequency caused by the ZnO film deposited using the Sauerbrey equation [8]. The dependence could be fit by a straight line:

$$d = 0.01123t - 0.17837, \quad (1)$$

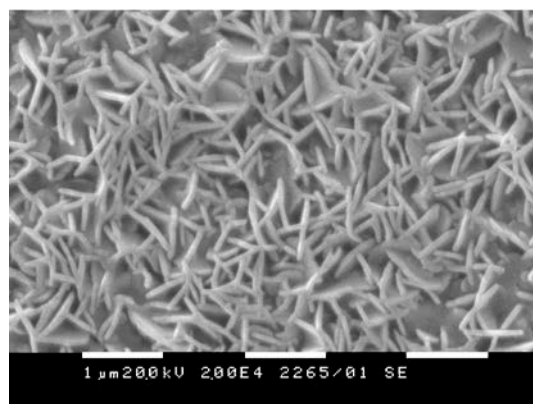
where  $d$  is the Sauerbrey thickness of the layer (in nm) and  $t$  is a the plating time (in minutes).

The slope of the line yields a value of the film growth rate of 11 nm/min. The negative term of equation (1) indicates a delay in the film growth onset (nucleation time), whose value (at  $d = 0$ ) is about 15 min [9].

Figure 2 shows a scanning electron microscopy (SEM) micrograph of a nanostructured ZnO thin film deposited at constant charge density for 60 min. The structure of this thin film consists of planar hexagonal ZnO nano-whiskers (NW) with a thickness of about 100 – 300 nm and different lengths (0.5 – 1  $\mu\text{m}$ ), stacked with the narrow side to the substrate surface. The thickness of the ZnO film is 0.5  $\mu\text{m}$ . The SEM micrograph reveals the porous surface morphology of the deposited layer.



**Figure 1.** Dependence of a ZnO film thickness deposited on a quartz resonator on the plating time.



**Figure 2.** SEM image of a ZnO layer deposited electrochemically for 60 minutes on a quartz resonator.

The ability of the ZnO thin films to sorb NO<sub>2</sub> was evaluated by the QCM method. For this purpose, the resonance frequency shift was measured. The sorption process was investigated in a gas flow of NO<sub>2</sub> with a concentration of 500 ppm by following the change in the frequency,  $f$ , of the QCM as a function of the mass loading. Figure 3 shows this change as a function of the exposure time. The highest rate of frequency change,  $S_p = 11.5$  Hz/min, was registered in the first two minutes. After that, the rate decreased more slowly, with the frequency reaching a constant value within about five minutes after exposure to NO<sub>2</sub>. When the gas flow was switched off, the frequency returned to its initial value within two minutes due to the desorption of the gas, the fastest change occurring in the first minute. The rate of change was calculated for the first five minutes after exposure to the NO<sub>2</sub> in order to estimate the sensitivity of the electrodeposited ZnO layer. The average value of the frequency-change rate,  $S_p$ , and of the total sorbed mass,  $\Delta m$ , were evaluated on the basis of the time-frequency characteristics measured using the relationship between  $\Delta f$  and  $\Delta m$  for AT-cut quartz plates as given by the Sauerbrey equation [6, 8]:

$$\Delta f = -(2,26 \times 10^{-6} f^2 \Delta m)/A, \quad (2)$$

where  $f$  (MHz) is the frequency of the QCM before exposure to NO<sub>2</sub>,  $\Delta m$  (g) is the mass of the gas sorbed on the surface of the ZnO films, and  $A$  (cm<sup>2</sup>) is the surface area of the Au electrodes. In our experiments, the frequency shift measured,  $\Delta f$ , was 38 Hz, and the sorbed mass,  $\Delta m$ , was calculated to be 8.39 ng. The  $S_p$  value of 7.6 Hz/min was calculated as the ratio of the frequency shift to the time of saturation (five minutes).

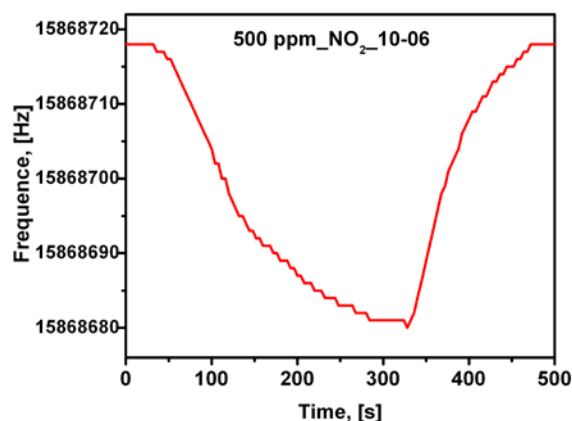
The electrochemically-deposited ZnO layer with grown nano-wiskers had a highly developed surface interacting with the NO<sub>2</sub> molecules. When the concentration of the gas in the chamber is raised, the NO<sub>2</sub> molecules are adsorbed in the ZnO layer; as a result, the resonator's mass increases and its frequency decreases. When the gas flow in the chamber is stopped, the NO<sub>2</sub> molecules start desorbing and the frequency of the quartz resonator returns to its initial value.

#### 4. Conclusions

The sensing characteristic to NO<sub>2</sub> of nanostructured ZnO layer electrochemically deposited on the surface of a QCM was studied. The structure of the ZnO layer, as revealed by SEM, consisted of nano-whiskers and had a developed surface morphology. The NO<sub>2</sub> mass sorbed in the ZnO layer at room temperature and 500 ppm concentration of the gas flow was calculated from the change in the frequency of the QCM after exposure to NO<sub>2</sub>. The change in the frequency reached saturation within five minutes after exposure to the NO<sub>2</sub> flow; the absorbed mass was calculated to be 8.39 ng. The time of frequency recovering once the gas flow is switched off was high – about 2 minutes. The results obtained demonstrated a potential application of the electrochemically-deposited nanostructured ZnO layers as room-temperature gas sensors of NO<sub>2</sub>.

#### Acknowledgement

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**Figure 3.** Frequency-time characteristic of a quartz crystal microbalance with an electrodeposited nanostructured ZnO layer under and after exposure to a 500-ppm NO<sub>2</sub> flow.

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