Energy requirements for methods improving gas detection by modulating physical properties of resistive gas sensors

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Abstract. One of the most important disadvantage of resistive gas sensors is their limited gas selectivity. Therefore, various methods modulating their physical properties are used to improve gas detection. These methods are usually limited to temperature modulation or UV light irradiation for the layers exhibiting photocatalytic effect. These methods cause increased energy consumption. In our study we consider how much energy has to be supplied to utilize such methods and what kind of additional information can be gathered. We present experimental results of selected resistive gas sensors, including commercial and prototype constructions, and practical solutions of modulating their physical properties.

1. Introduction

The majority of resistive gas sensors start to be gas sensitive at elevated temperatures only, reaching even a few hundred Celsius. It means that such sensors require continuous energy supply for their heating. The electrical power necessary for heating commercial resistive gas sensors (e.g. Taguchi gas sensor TGS 823) is close to 0.7 W for more stable constructions, giving reliable gas detection results. Less precise sensor constructions (e.g. TGS 2600) require about 0.2 W only [1, 2]. Their physical properties, like intensity of adsorption-desorption processes of ambient gas molecules, will change respectively to their operating temperatures. This means that a change of heating power can modulate sensor DC resistance and this phenomenon can be utilized to improve gas detection. We can expect that resistance fluctuations (1/f-like noise) change at different temperatures as well as DC resistance. Thus, a method of fluctuation enhanced sensing (FES) used for gas detection since a decade can be also applied at different temperatures to gather more information [3, 4]. This study will compare experimental results of both mentioned methods observed for a few investigated commercial sensors and selected gases.

Some resistive gas-sensing layers (e.g. \(\text{WO}_3\), \(\text{TiO}_2\) [5, 6]) exhibit a photocatalytic effect when irradiated by UV light. Application of that effect is often limited to sensor cleansing only but it can be utilized to modulate gas sensitivity and selectivity as well. We can suppose that such method should be quite efficient because of limited energy consumption and measurement time, especially when compared with the results obtained by temperature modulation. Both issues will be considered in the paper to give an overview of which method could be more efficient for portable gas detection systems.
to improve their detection efficiency when energy consumption is one of the most important parameter.

2. Effectiveness of temperature modulation

An elevated temperature of the resistive gas sensor is secured by supplying DC voltage to its heater (typically 5 V for commercial gas sensors). Thus, any change of that voltage will result in a change of sensor temperature determined by the thermal inertia of the sensor. Experimental results for exemplary commercial gas sensor and selected gas mixtures suggest that changes of the sensor’s DC resistance at stepwise change of DC voltage depends on gas sensor ambient atmosphere (Figure 1). Similar results were published by other authors [7, 8]. Time constants related to dynamic changes of the sensor DC resistance (initial increase and further drop) or position and level of its maximum would secure additional parameters, determined by ambient gas atmosphere (the chemical time constant is slower). Such parameters can be estimated by observing DC resistance changes during time interval at least about 60 s according to exemplary experimental results (Figure 1) and applied in popular detection algorithms [9]. It means that we have to heat up the sensor and have to spend energy equal to at least 0.2 W·60 s = 12 J. In a case of a more stable commercial gas sensor (e.g. TGS 823) the required energy will be even a few times greater.

Figure 1. Change of DC resistance $R$ of commercial gas sensor TGS 2600 at ambient atmosphere of the selected gas mixtures (CO and NH$_3$ diluted in synthetic air) normalized to its resistance $R_0$ observed at synthetic air versus time $t$; a stepwise drop of heating voltage from 5 V to 4.7 V was applied at $t = 60$ s.

The presented method of applying temperature modulation for better gas detection utilizes rather a small change of heating voltage and therefore additional time of measurement is relatively short and energy necessary for the prolonged heating is limited as well. The method is quite efficient to observe changes of DC resistances characteristic for different gases. When we observed 1/f-like resistance noise at the same heating voltage drop the results cannot be used for better gas detection. There was almost no change in intensity of 1/f-like noise at the drop of heating voltage from 5 V to 4.7 V, at least in a case of investigated gases (CO, NH$_3$, CH$_4$). Thus we have to apply other measurement conditions which could utilize the FES method. That issue has been considered recently by changing sensor temperatures at wider range and resulted in much prolonged measurement time [10, 11]. One of these methods estimates power spectral density of 1/f-like sensor resistance noise at different temperatures and observes a change of maximal noise intensity (power spectrum density at the selected frequency) at different temperatures due to various rates of adsorption-desorption processes [10]. That change is
characteristic for the ambient gas and can be utilized to determine its presence. The method requires noise measurements at a few temperatures of the gas sensor. We have to continue such measurements at least an hour and to heat the applied sensor all time [10]. It means that the supplied energy will be many times greater than the energy necessary to record DC dynamic changes as presented in Figure 1. Moreover, recording of resistance noise requires more advanced measurement setup than for measurements of DC resistance only and additional energy consumed by that system, even if the system is limited to selected frequency bands (e.g. as proposed for toxic gases detection [12]).

Another method when resistance noise can be utilized to improve gas sensing by its measurements at different temperatures is a method called sample-and-hold [13]. The method keeps the gas sensor at its operating temperature at ambient atmosphere of the investigated gas and cools to room temperature to keep the “frozen” gas species inside the porous gas-sensing layer structure. Next, the sensor is slowly heated when placed in atmosphere of synthetic air only. Changes of resistance noise intensity during heating can be used to detect the type of the “frozen” gas species. Especially, temperature value when the “frozen” gas species evaporate from the porous gas sensing layer due to desorption processes depends on energy activation of the investigated gas [11]. That method ensures high selectivity for the detected gas but requires at least 1-2 hours of slow gas sensor heating. Thus, both presented methods utilizing resistance noise measurements at various temperatures require many times more energy than the method recording DC resistance changes induced by a change of heating voltage. It means that only the last method could be applied in portable applications due to energy consumption even if the FES methods at modulated temperatures ensure a higher selectivity for the detected gas.

3. Effectiveness of UV irradiation
Some gas sensing materials (e.g. WO$_3$, TiO$_2$) exhibit a photocatalytic effect when irradiated by UV light [5, 14, 15]. That effect is often used to cleanse the gas sensor instead of using heating pulse because it is often faster and more energy efficient than the heating pulse [5]. The main disadvantage of that method is the need for an additional UV LED-diode. These diodes are characterized by different wavelengths of maximal optical power emission but require relatively small power consumption to be used (e.g. maximally 4 V × 10 mA = 0.4 J/s for exemplary diode T5F36).

In our experimental studies we have applied the diode T5F36, having maximal emission at about 362 nm (Figure 2). The UV diode could be biased up to 10 mA but a photocatalytic effect present in the investigated material was observed at lower currents.

![Figure 2. Optical power of the applied UV LED-diode T5F36 when biased by DC current $I_d = 5$ mA; the diode was placed at the same distance from the power meter as in a case of measurements of gas sensing WO$_3$ layer.](image-url)
The prototype gas sensing layer of WO$_3$ was investigated. All details of their preparation and parameters are presented elsewhere [15]. The gas sensing layer was irradiated by the diode placed about 5 mm from the gas sensing surface. We have observed that the diode current $I_d$ limited to a few mA was sufficient to saturate effects of the DC resistance changes induced by the emitted UV light (Figure 3). A relative change of DC resistance induced by UV irradiation depended on the ambient gas and reached even 35%. That change was more intense in comparison with relative changes of DC resistance induced by drop of heating voltage (e.g. change of its maximum value – Figure 2). The DC resistance has stabilized about 10-15 min after switching on the UV LED-diode. It means that the UV-light can replace temperature modulation to improve gas detection, at least for some gases and for the gas sensing layer exhibiting photocatalytic effect. Moreover, that method requires similar amount of energy ($600 \text{s} \times 4 \text{ V} \times 5 \text{ mA} = 12 \text{ J}$) as in a case of temperature modulation method (Figure 1) but means a use of additional element – UV LED-diode.

![Figure 3](image_url)

**Figure 3.** Changes of the normalized DC resistance $R$ of WO$_3$ gas sensing film [15] versus UV LED-diode DC current $I_d$ at two different gas mixture concentrations of NO$_2$ and C$_2$H$_5$OH, at working temperature of 200°C; $R_0$ – DC resistances observed for the selected gas mixtures at $I_d = 0$ mA.

Our preliminary studies of 1/f-like resistance noise changes induced by UV light in the investigated WO$_3$ gas sensing layer suggest that noise measurements depend strongly on UV light and can be used to improve gas detection [15]. Noise intensity has changed even ten times when UV light was used to modulate the gas sensing layer. Unfortunately, the FES method is not so energy efficient than DC resistance measurements only. It requires energy for noise amplification, sampling, recording and necessary computing but can potentially assure much more information for detection algorithms when compared with the DC resistances at modulated conditions [16-18]. The 1/f-like noise is often used as a source of information about various materials and their qualities [19, 20]. Thus, effectiveness of noise measurements for gas detection has to be considered separately for each case. We can only conclude that the method of gas detection based on measurements of DC resistances modulated by temperature or UV light consume less energy when compared with the FES method.
4. Conclusions
In our experimental study we have presented and analysed exemplary data of DC resistance changes at different temperatures or modulated by UV light. The results suggest that UV light can be utilized for better gas detection in portable systems because of energy consumption. We can suppose that even better gas detection can be obtained when the $1/f$-like noise is used for gas detection when the sensor is modulated by UV light. Unfortunately such improvement requires more energy and more sophisticated measurement system. Further experimental studies are necessary to answer this question for gases of interest. Moreover, smaller gas sensors means their faster response and shorter measurement time. We can conclude that even without applying smaller sensors the measurement time can be reduced by cost of lower accuracy. The compromise between accuracy and measurement time requires more detailed studies.

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