A Zinc Oxide (ZnO) gas sensor approach to detect oxidizing gases

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Abstract. Selective detection of gases such as nitrogen dioxide (NO_2), carbon monoxide (CO), carbon dioxide (CO_2), and various volatile organic components is necessary for air quality monitoring and for safety. There are several metals oxide gas sensor (MOGS), but the focus of this study was Zinc Oxide (ZnO); an n-type MOGS. NO_2, an oxidising gas was the target gas. The aim of this study was to establish the possible enhancement of a gas sensor selectivity by the introduction of signal conditioning electronics circuitry such as the Wheatstone bridge in tandem with an operation amplifier circuit. Exposing electronics enhanced ZnO MOGS system to NO_2 resulted in a negatively increasing voltage output between 0 and – 3.5 V. This range of voltages is sufficient to run a micro-controller, with the assumption that a reducing gas would result in a positively increasing voltage, a micro-controller could be conditioned to select between an oxidising and a reducing gas.

1. Introduction

Metal Oxide Gas Sensor (MOGS) when exposed to gaseous chemicals may respond in such a way that their resistivity changes with concentration of the gas. ZnO is an n-type MOSG that works on chemo-resistance principle and NO_2 is an oxidising gas. When ZnO is exposed to NO_2 the following chemical reaction takes place.

$$\mathrm{NO}_{2(gas)} + e^-_{(surface)} \longrightarrow NO^-_{2(adsorbed)} \quad (1)$$

$$\mathrm{NO}_{2(gas)} + O^-_{2(adsorbed)} + 2e^-_{(surface)} \longrightarrow NO^-_{2(adsorbed)} + 2O^-_{(adsorbed)} \quad (2)$$

Electrons are taken away from the surface leading to increased resistance of the ZnO MOGS. For this project, the gas sensor was introduced in a Wheatstone bridge which was designed to balance with no gas present. The Wheatstone bridge equation (3) was captured in excel to allow comparison between simulated and theoretical results.

$$V_{out} = \left(\frac{1}{1 + \frac{R_2}{R_1}} - \frac{1}{1 + \frac{R_3}{R_4}} \right) \quad (3)$$

Gas sensor is a device that receives a signal such as chemical signal and responds or converts into an electrical signal. Gas sensor is mandatory tool that is used to identify a specific task assigned to it [1]. In this experiment gas sensor was a semiconductor (ZnO) device that will be used to senses toxic gases in our industry or working place. The aim was not to measure the resistance of the gas sensor in the presence of the targeted gas, but rather than measure the output voltage of the gas sensing system.

1.1. Zink Oxide as a gas sensor

Over the past decade, scientist have seen important improvement in the quality of ZnO as an electronic material in its own right. The detection of gas is enabled by using semiconductor sensors that are selective for particular chemical species [2]. The sensors that have been made give a response to mixed gases. This means that those sensors are not selective enough to that specific chemical species. This problem has been solved by introducing sensor array that can simultaneously detect specific gaseous chemical species made possible by giving the correlation among huge amounts of sensor output [3].

A ZnO is a kind of material that is widely used in electronic and opto-electronic applications because of its abundance, non-toxicity and low cost[4]. ZnO is a well-known material that is a II-VI compound semiconductor with a wide band gap energy semiconductor of $3.37eV$ [5]. The response of the ZnO gas sensor toward some targeted gas may be upgraded by using doping, reducing grain size or changing the temperature and humidity [6]. The crucial characteristic that manufacturers need in a gas sensor is for it to be selective with respect to the type of the targeted gas that is oxidizing or reducing [7].

The metal oxide gas sensor works on chemo-resistance principle. When the gas molecules interact with metal oxide surface, it acts as either an acceptor or donor. The resistivity or electrical conductivity of metal oxide thin film changes as it interacts with the target gas. The resistivity of the metal oxide semiconducting thin film depends on the majority carrier in the film. This happens if it is oxidized or reduced in the ambient temperature [8]. Gas molecules undergo Reduction-Oxidation (REDOX). A surface adsorption site ensures correct interaction of gas molecules with the material. The adsorption can be observed by tempering with temperature. Below 200°, oxygen can accept one electron and above 200° it can accept two, as shown by equation (4) and (5) [9]. In the case of n-type, the surface get depleted with electrons by appearance of any other ions such as oxygen and upon exposure to the target gas, these species react with gas molecules to reverse back electron on the surface, resulting in decreasing conductivity [10].

$$\mathrm{O}_{2(gas)} + e^-_{(surface)} \Longleftrightarrow O^-_{2(adsorbed)} \quad (4)$$

$$\mathrm{O}_{2(gas)} + 2e^-_{(surface)} \Longleftrightarrow 2O^-_{(adsorbed)} \quad (5)$$

1.2. Synthesis of ZnO MOSGS thin films

Since there are so many methods used to deposit ZnO for different application, the chemical bath method is the preferred one over other methods because it is simple, requires low temperatures, low cost of deposition and does not need expensive equipment. In this paper, thin films of ZnO have been deposited on silica glass substrate using chemical bath method. It investigated two things, the chemical composition and the morphology of the film and the band gap and the effect of annealing temperature on the band gap [11].

1.3. Description of an existing device

The gas testing chamber was made in a way that it may endure extreme hot temperature. Temperature was varied in order to establish the effect of temperature on the sensitivity of the sensor to the test gas. The chamber was made from brass and had a transparent lid to allow for easy monitoring of all connections.
The gas testing chamber has a stage inside that is capable of heating up the sample to a desired temperature. The stage is made up of 6×33kΩ resistors with a power rating of 10W and a thermo-couple to measure the temperature of the stage. The stage temperature is controlled by adjusting the voltage from power supply.
It has two pipe inlet of gases, the test gas and the flushing gas. It has one pipe outlet that removes the gas inside the chamber. This is immersed into water to reduce possibilities of explosion.
The stage is made to carry the sample that may be used for gas sensing application. A sample is on the substrate that had Silver contact with a copper wire connected to a Tru-RMS multi-meter used to measure the test gas effect on the resistance of the samples.

1.4. Proposed concept

The objective of this study is to modify an existing sensing device [12]. An output voltage in a range of 0 V and 5 V is required to run a micro-controller that monitors the test gas as it is introduced in the gas sensing device.

1.5. The Wheatstone bridge circuit

The Wheatstone bridge and its governing equation shown below; a gas sensor is designed when it is exposed in air for an oxidising gas, the sensor resistance is at the maximum. To monitor

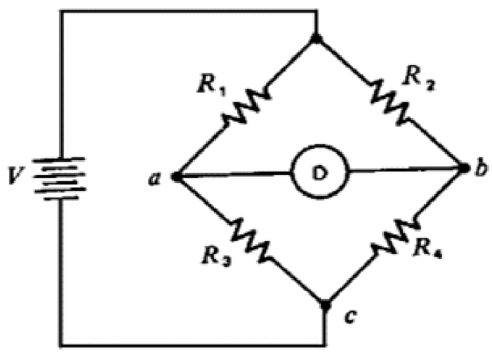

Figure 1. Wheatstone bridge.

the gas inside and outside of the chamber two of the gas sensors are used and placed at the R_1 and R_3, as in figure 1. The Wheatstone bridge was designed to balance at gas sensor resistance obtained when it is placed in air. This serves as the normalising resistance and at this resistance value, the output voltage of the bridge is zero.

2. Design and simulation using P-spice

The connection of the Wheatstone bridge and the circuit with an Operation Amplifier (OpAmp) is shown in figure 2. The OpAmp at the output port of the Wheatstone bridge obtain the

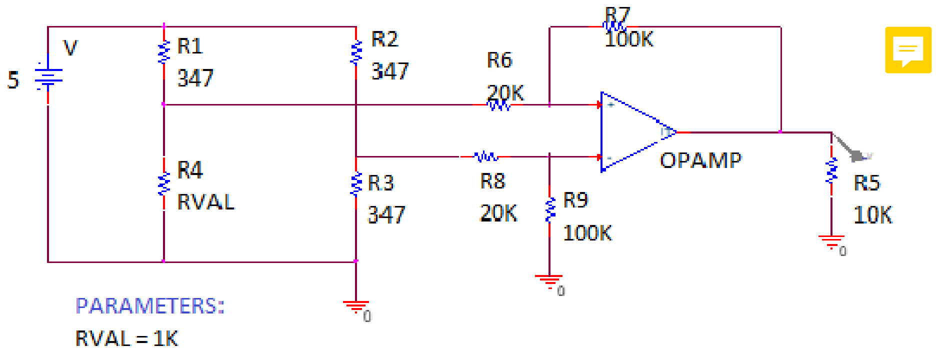

Figure 2. The schematic diagram of proposed concept in p-spice.

output voltage from the bridge and amplify it to a voltage suitable for micro-controllers. The Wheatstone bridge was designed to balance with the gas sensor not exposed to the target gas and inside R1 and R4 respectively resistance targeting R3 because the outside gas sensor placed in air acts as a normalising gas sensor. In the circuity of Figure 2, the ratio $\frac{R_7}{R_6}$ or $\frac{R_9}{R_8}$ determines the amplification factor of the amplifier.

2.1. Sensor resistance and the balancing of the Wheatstone bridge

Using the result presented by Shichi Seto et al [7] on the paper of Mathematical modelling of semiconductor on gas sensor, the change in gas sensing resistance was used to test the proposed concept. At 350°, the RVAL of the sensor increase from about 347 Ω in the presence of air to 625 Ω in steps of 5 Ω in the presence of the targeted gas.

3. Results and discussion

Figure 3 shows results obtained from P-Spice simulations compared with those obtained theoretically using mathematical models in Excel

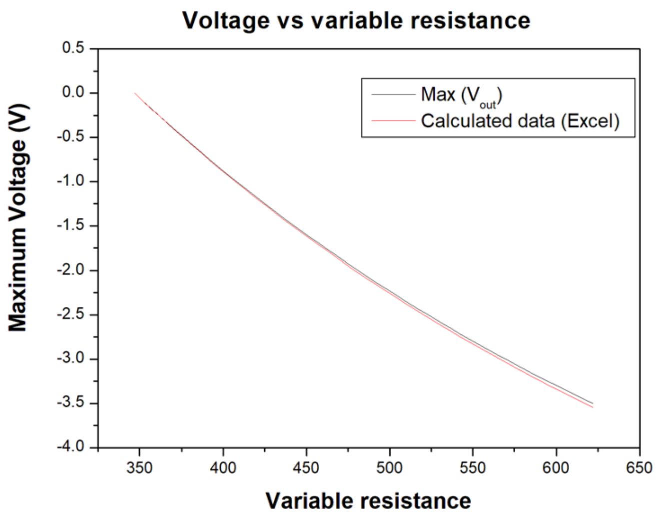

Figure 3. Readings of the maximum output voltage in the variable resistor. The graph shows the negative increase as the gas enters the chamber.

The graph shows the negative increase of voltage as the gas enters the chamber. Result clarifies that this is the oxidizing gas, increasing resistivity with reducing conductivity. The voltage magnitude lies between 0 V and -3 V and is sufficient as an input to a micro-controller. As two curves are embedded to each other, it clarifies that simulated circuit in p-spice result sympathize with a calculated result.

4. Conclusion

The designed circuit was successful in providing the required voltage for the micro-controller, falling between 0 V and -3.5 V. Results shown above compliment the theory of oxidizing gas as a negative increase voltage. Results from simulated circuit in p-spice agree with the result from calculated result (Excel). It also comply for reducing gas as my colleague got positive values of voltage showing that the test gas was reducing gas decreases the resistivity. It is recommended that with ZnO MOGS in a Wheatstone bridge connected to an operational amplifier in tandem with a micro-controller would enhance its selectivity of oxidizing or reducing gases.

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