Enhancing Zinc Oxide gas sensing device for microcontroller application

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Abstract. Zinc Oxide (ZnO) gas sensors have been popular for some time now, responding with change of sensor resistivity in the presence of a reducing or oxidising gas. The presence of a reducing/oxidising gas is indicated by a measured change in resistance in a gas sensing environment developed at the University of Zululand in the physics department. The purpose of the project was to convert changes in resistance to voltage changes that lie between 0 V to 5 V, suitable for microcontroller applications. Formaldehyde (HCHO), a reducing gas was used to investigate changes in resistivity of the gas sensor in order to establish the range of measured resistance which varied from 1380 to 420 ohms in the absence or presence of the HCHO respectively. Design of a suitable circuit was done, this included the choice of Wheatstone bridge resistances in tandem with a difference operational amplifier. A P-spice simulation environment was developed and used to asses the designed circuit for its suitability for the required voltage range. Simulation results showed that the design circuit provides 3.25 V and 0.13 V in the presence and absence of the gas respectively. This results show that a microcontroller can be introduced to the circuit to give alerts.

1. Introduction

Zinc Oxide (ZnO) as a typical semiconductor metal oxide gas sensor, exhibits characteristics needed for a perfect gas sensor. These include wide band gap of 3.37 eV, large exciton energy of 60 meV, high electron mobility, photoelectric response together with excellent chemical and thermal stability [1, 2, 3, 4, 5, 6]. ZnO is low-cost, non-toxic and easy to prepare [7]. Moreover, ZnO could be a typical chemo-resistive sensing material as its gas sensing is dominantly controlled by the change in sensor resistance when gas molecules react with its surface [8]. In a surrounding atmosphere, oxygen molecules are adsorbed (attached) on the surface of ZnO which then ionizes into oxygen species by capturing electrons from the conduction band, resulting in the formation of surface depletion layer and thus increasing the sensor resistance. When a reductive gas like acetone, approaches ZnO surface, oxygen species will interplay with these gas molecules and release trapped electrons back to the conduction band, causing the sensor resistance to decrease [9, 10]. While exposure to oxidising gases like NO_2 act as electron acceptor, the sensor resistance increases instead [11, 12]. Hence, it is the variation in sensor resistance that achieves the gas sensing characteristic.

Since HCHO is a reducing gas, it will act as an electron donor when interacting with the Zinc Oxide surface. Oxygen ions will be desorbed (released) from ZnO during the interaction and OH ions physisorbed (attached) to the metal oxide (ZnO) surface. As this interaction occurs there will be a variation of resistance in ZnO [13]. The adsorption of oxygen creates ionic species such as O^{2-}, O_2^-, and O^-, which acquire electrons from the conduction band [14]. The reaction kinetics for creation of the ionic species are as follows:

$$O_2(\text{air}) \longleftrightarrow O_2(\text{adsorb}) \tag{1}$$

$$O_2(\text{adsorb}) + e^- \longleftrightarrow O_2-(\text{adsorb}) \tag{2}$$

$$O_2(\text{air}) \longleftrightarrow 2\,O-(\text{adsorb}) \tag{3}$$

The HCHO molecules react with created oxygen species releasing trapped electrons back to the conduction band of the zinc oxide semiconductor, that will increase carrier concentration and electron mobility that will lead to a decrease in resistance of a gas sensor. The reaction is described below [15]:

$$HCHO + 2\,O-(\text{adsorb}) \longrightarrow CO_2 + H_2O + 2\,e^- \tag{4}$$

For this project, the main aim was to improve the sensitivity of the electronics used to sense the small resistance changes associated with ZnO gas sensors and to convert it to an output voltage in the range of 0 to 5 V, suitable for microcontroller application. The P-spice [16] simulation (Cadence's electronic circuit simulation tool) environment was used to evaluate the design concept to provide recommendations for the next stage of development.

1.1. Synthesis Of ZnO

Zinc oxide is a known metal oxide semiconductor gas sensor, because of its wide band gap energy. Numerous processes have been used to deposit ZnO on substrates for certain applications such as spin coating, spray pyrolysis technique, thermal evaporation and DC magnetron sputtering [17]. At the department of Physics and Engineering at the University of Zululand, one of the methods used to synthesise ZnO thin films is the chemical bath technique. This method doesn't need sophisticated equipment, uses low temperature and has low cost of deposition [17]. Samples to be used for the devices being considered for this project was synthesized using this technique [18]. The samples provided for this project were ZnO thin films with gold contacts applied.

2. Design Process

2.1. Description Of a Test Chamber

The existing test chamber [18], shown in figure 1 contains the targeted gas introduction under controlled conditions taking cognizance of safety related to explosive gases. The chamber made from brass, allows constant visual monitoring (window in the chamber lid) of the sample gas sensor and controlling the temperature inside the chamber. Inside the test chamber, there is a stage that is capable to heating up to desired temperature and also a thermocouple that monitor the temperature. The chamber consists of an inlet for the introduction of the required test gas volumes, gas outlet and also nitrogen line for flushing the chamber. The test chamber circuit was replaced with a Wheatstone bridge circuit so that the output voltage can be measured instead of a resistance. All other components in the test chamber were kept the same.

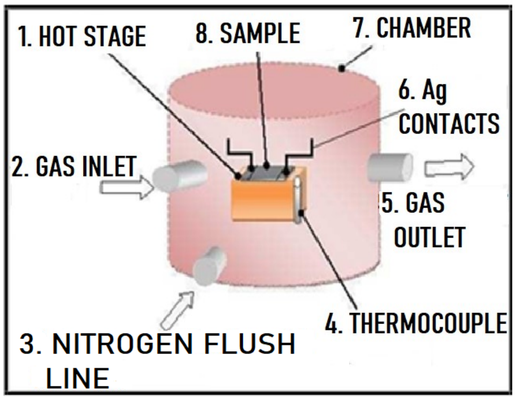

Figure 1: Schematic of the test chamber of ZnO samples as function of temperature and test gas. [18]

2.2. P-spice Circuit Simulation

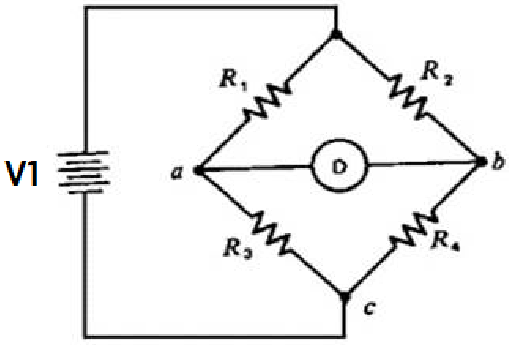

Figure 2: Schematic of a Wheatstone bridge

For the simulation a Wheatstone bridge circuit was used to convert the changing in sensor resistance into change in the output voltage of the Wheatstone bridge. The general Wheatstone bridge circuit is shown in figure 2:

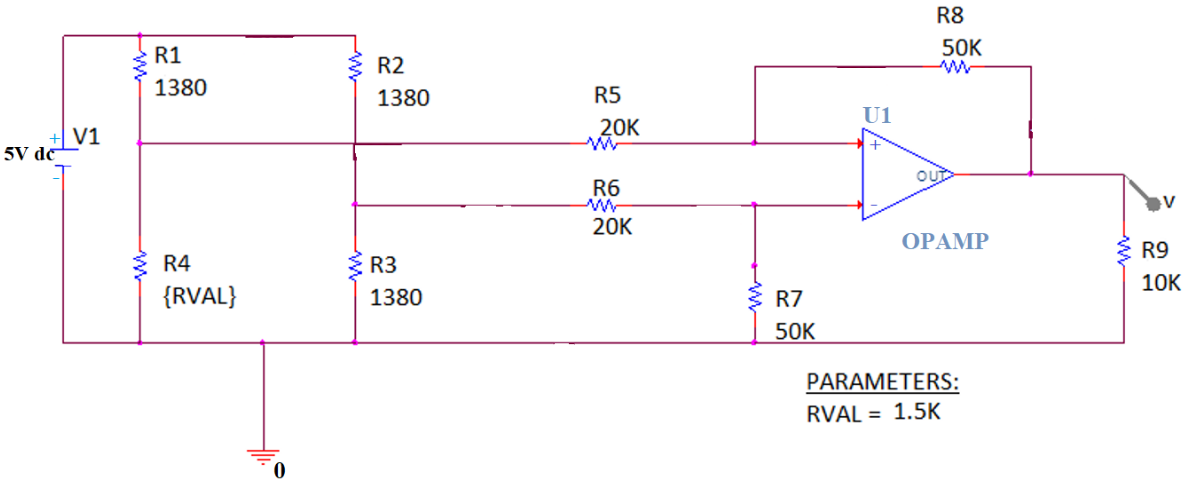

Figure 3: Proposed circuit design

In the Wheatstone bridge circuit, resistor R1 represents a sensor resistance in air and resistor R4 represents sensor resistance in a gas chamber. Resistors R2 and R3 are chosen to be equivalent to R1 in order to give zero output voltage when there is no gas according to equation (5). The difference operational amplifier (OpAmp) was introduced as shown in figure 3. Resistors, R5, R6, R7 and R8 are chosen to control amplification factor of the OpAmp circuit. The operational amplifier connected at the output port of the Wheatstone bridge amplifies the bridge output voltages to between 0 and 5 V suitable for micro controller application. The amplification factor is determined by resistor ratios R8/R5 or R7/R6. R1, the gas sensor resistance in air, has a value of 1380 ohms and R4 which is labelled as RVAL has values that varies with a gas presence.

The formulae used to calculate the output voltage of the OpAmp in Excel are shown below. Equation (5) is the output voltage of the Wheatstone bridge circuit and equation (6) is the amplification output voltage.

$$V_{th} = \left(\frac{1}{1 + \dfrac{R4}{R1}} - \frac{1}{1 + \dfrac{R2}{R4}} \right) V1 \tag{5}$$

$$V_{OpAmp} = \left(V_{th} * \frac{R8}{R5} \right) \tag{6}$$

3. Results And Discussion

3.1. Results

The graph below shows results obtained from the P-Spice simulations compared with those obtained through calculations using equation (6) in Excel:

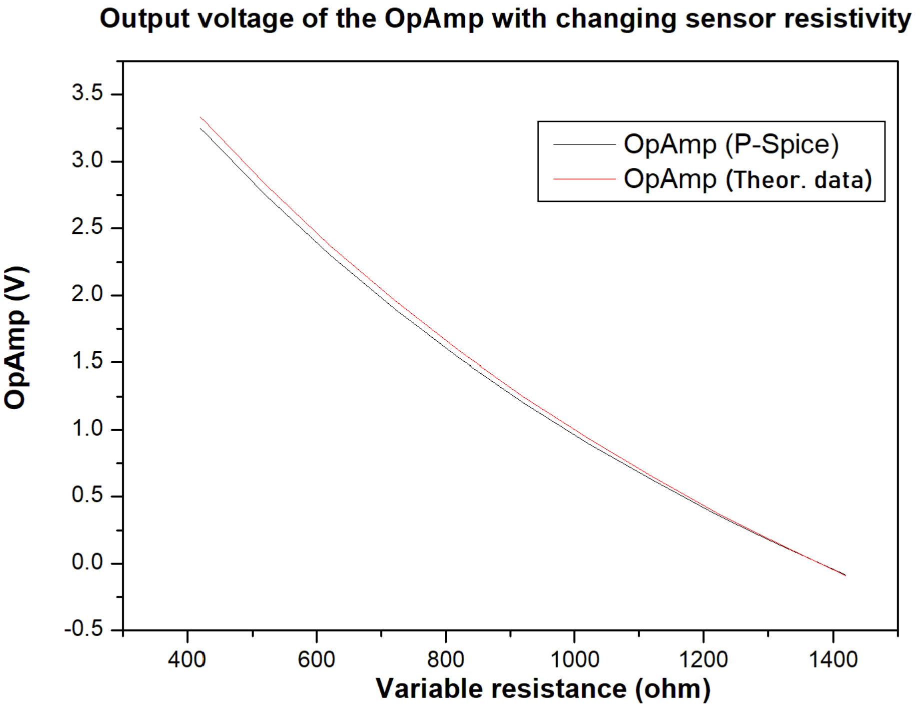

Figure 4: The graph comparing the result of Pspice and calculated data

3.2. Discussion

It was observed that the operational amplifier output voltage decreased exponentially as the gas entered the test chamber which implies the presence of a reducing gas. The resulting decrease in resistivity correspond to an increase in conductivity of the gas sensor. The output voltage magnitude of an operational amplifier lies between 0 to 3.25 V which is sufficient for microcontroller application. Figure 4 validates that the PSpice simulated results and the calculated results are very close to each other with a difference of $\pm 0.04V$.

4. Conclusion

By using a Wheatstone bridge in tandem with a difference operational amplifier, the electronic circuit simulated in P-spice was successful in providing the required output voltage, ranging from 0 to 3.25 V, that is suitable for microcontroller application. For HCHO, a reducing gas, a resistance of the ZnO gas sensor decreased in the presence of the target gas resulting in a decreasing output voltage from the simulated circuit. Results from Pspice correspond with theoretical data, therefore, the simulation was successful.

5. Future Work

In future, the respective effects from reducing and oxidizing gases will be integrated in a single design. A microcontroller will be introduced to the system to differentiate between gas types.

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