SPICE MODELING OF TAGUCHI SENSORS

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The detection and monitoring of gases with metal oxide type sensors is become a well-established practice. Modern signal processing systems are usually composed of a variety of components, electrical as well as nonelectrical (e.g. sensors and actuators, fibre optics). More complex technical systems and higher levels of integration of electronic circuits lead to new requirements on the design process of modern signal processing systems, especially on modeling and simulation. Besides multi-level-simulation of electronic circuits the analysis of nonelectrical components becomes very important for efficient system design. Methods for describing behavior of nonelectrical systems are essential for their modeling and simulation. This paper presents design methodology for analogue behavior modeling for describing the behavior of metal oxide type sensors for SPICE based simulators, which initially come from the field of circuit simulation. Simulation results of an example gas monitoring system are shown.

Keywords: Behavior Modeling, Sensor Systems, SPICE Simulation, Taguchi Gas Sensors.

1. INTRODUCTION

Depending on the environment, the air may contain various chemical pollutants or volatile organic compounds. Some of these pollutants are either explosive (like methane and LP gases) or highly toxic (like carbon monoxide). Living in the contemporary industrialized world requires the protection against influence of these substances, what induces the need for continuous monitoring of the specified compounds. However the precise instrumental analyses are very expensive and time consuming. The achievements in microelectronics provided the development and massive production of low-cost semi conductive sensors, based on gas sensitive materials changing its resistance and/or impedance when hazardous substances appear in the air [2, 7].

On the other hand the activity in the field of computer-aided design in engineering of electrochemical gas sensors has been increasing steadily over the last decade. A vast range of models exists today, varying in complexity and in the number of assumptions employed. However, the emphasis in a majority of the models has been either on the transport processes or on the electrochemical processes.

There are two types of gas sensors' model approaches: finite element modeling and system level modeling. First one is used to predict nonelectrical responses applied to a sensor [1]. There are many software tools suitable to gas sensors simulation. Can be listed CoventorWare, IntelliSuite, ANSYS, MEMSCAP with build in SMASH VHDL-AMS simulator etc.

The system level modeling captures the main characteristics of sensor and provides a quick method to predict the main behavior of a device. As more popular behavioral modeling tools can be mentioned Matlab's Simulink, VisSim, Saber from Synopsis etc. ABM (analog behavioral model) sources use mathematical and conditional expressions to set theirs output voltage or current. They may contain mathematical and conditional expressions that consist of circuit voltages, currents, time and other simulation parameters. ABM is an extremely powerful feature, which provides an efficient way to macro-model signal processes through non-linear mathematical and conditional expressions like sensor's calibration curve. A lot of analogue behavioral blocks exist in PSpice based software and allow modeling the analogue behaviors of components with block diagrams [4].

Generally, behavioral models make simulations much faster, compared to finite element modeling. But there is a trade-off between performance and accuracy. Highly accurate models usually require significant development effort, and complex models take longer to simulate compared to simple ones.

In this paper a generalized PSpice model of resistive gas sensors is presented. In order to harmonize the high level of integration system with SPICE simulations the use on ABM is suggested. The model simulates the response of the metal oxide device, as well as an integrated resistive heater that is used to set the operating temperature.

2. BASE CHARACTERISTICS OF TAGUCHI GAS SENSORS

Metal oxide has recently received a great scientific interest because of its wide range of applications [2, 3]. The working principle of metal oxide or Taguchi-type of semiconductor gas sensors is based on the variation of conductivity in presence of oxidizing and reducing gases. This type of sensors represents a low-cost option to the standardized and bulky methods (e.g., gas chromatography or mass spectroscopy). Mostly metal oxides, SnO_2, TiO_2, ZnO, Mn_2O_3 and WO_3, are used as sensor materials.

The gas sensor specific parameters are: sensitivity, selectivity, robustness, response time, long term effects and the temperature of the sensor surface.

The first parameter, *sensitivity*, is the ability to detect small concentrations of a gas. Typically sensitivity is measured as the slope of the response curve (also known as the calibration curve). This term is also used to refer either to the lowest level of chemical concentration that can be detected or to the smallest increment of concentration that can be detected in the sensing environment. Sensitivity S_d is defined by the resistance R change when the sensor is exposed to a certain concentration C of gas as [3]:

$$S_d = \frac{\partial R}{\partial C} \,. \tag{1}$$

The relative sensitivity, in the case of resistive gas sensors, is defined as the ratio of the resistance of the sample measured in a reference gas R_0 (usually air or synthetic air) to the target gas-containing atmosphere R_S. The most usually used expressions for relative sensitivity S for an n-type gas material like SnO_2 and for reducing gases is:

$$S = \frac{R_S}{R_0} \ . \tag{2}$$

In general, it is observed that resistance changes rapidly with increasing concentration of a target gases in air. So, a small quantity of uncontrolled gas in the chamber or at the surface of the sensor can produce a large error in the measurement of gas response.

Selectivity, or the ability to distinguish between gases, is the second parameter that defines a sensor. Selectivity of resistive gas sensors is still a major problem to be solved. Unfortunately, the selectivity of the metal oxide gas sensor is broad, responding to all reducing gases that interact with oxygen on the surface of the sensor. In this framework, catalytic additives can lead to an improvement of the sensor activity by means of a selective promotion of a desired molecule reaction in a chosen site. Moreover, the appropriate catalytic element modifies the temperature of response of the sensing material to the desired target gas [2, 3].

Robustness at the sensor level refers to the ability of the sensor to perform its function over a range of ambient condition e.g. humidity, temperature etc. and over a range of times in the presence of drift and stability variations. Unfortunately, the parameters of a chemical sensor technology that can be adjusted to improve robustness are often the same parameters that result in a decrease in sensitivity and selectivity. A fine balance between the robustness and sensitivity can be overcome by using both engineering and science.

In gas detection, *response time* is usually defined as the time taken to achieve 90% of the final change in conductance following the step change in gas concentration at the sensor.

Long term effects refers to the conductance of the sensor in clean air. Changes over long operating times of both baseline and sensitivity are all-important in utilization of the sensors. These determine the frequency at which the calibration checks should be carried out and the frequency at which the sensors may have to be replaced. They can only be determined over long periods of time and no method by which the process can be accelerated is valid.

The *temperature of the sensor surface* is one of the most important parameters. Firstly, adsorption and desorption are temperature activated processes, thus dynamic properties. The surface coverage, co-adsorption, chemical decomposition or other reactions are also temperature dependent, resulting in different static characteristics at different temperatures. On the other hand, temperature has an effect on the physical properties of the semiconductor sensor material such as charge carrier concentration, Debye length, work function etc. The optimum range of temperature for an effective sensor response corresponds to that where the material is able to catalytically reduce or oxidize the target gas, simultaneously changing the electrical properties of the sensor material. The built-in heater, which heats the metal oxide material to an operational temperature range that is optimal for the gas to be detected, is regulated and controlled by a specific circuit.

3. DEVELOPMENT OF ANALOG BEHAVIOR MODEL

The ABM feature of PSpice can be used to make flexible descriptions of electronic components in terms of a transfer function or look-up table. In other words, a mathematical relationship is used to model a circuit segment, so the user does not need to design the segment component by component. Device models using this ABM capability are well suited for use with measured or catalogue data [4].

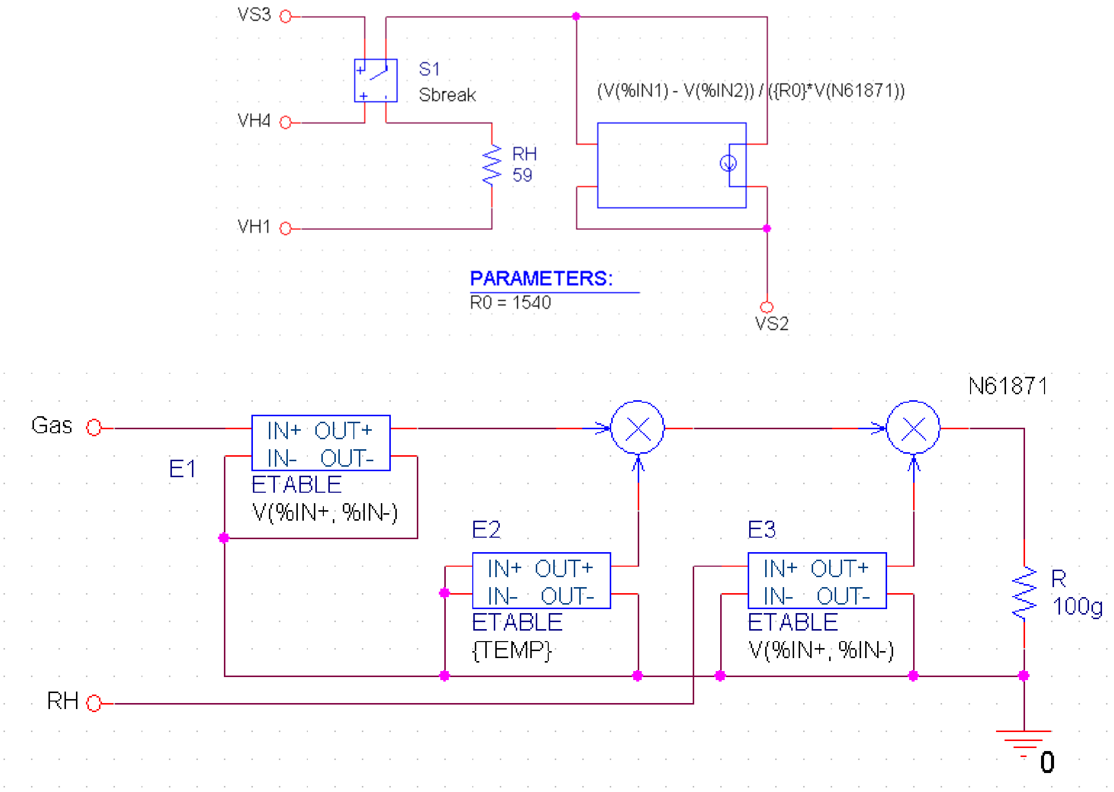

Fig. 1.The basic structure of the gas sensors ABM model

The basic structure of the gas sensors ABM model is shown in fig. 1. The main parts of the proposed model are:

1. E1 – ABM table part ETABLE is used for modeling the relative sensitivity of the sensor using the calibration curve given by manufacturer in the datasheet characteristics. The table consists of pairs of values, the first of which is an input (corresponding to the gas concentration), and the second of which is the corresponding output (corresponding to the relative sensitivity of the sensor). The obtained output voltage is equivalent to the relative sensitivity over the simulated gas concentration.

2. E2 and E3 – ABM table parts ETABLE are used for modeling the environment influence over the behavior of the sensor (the robustness at the sensor level). For many sensors such influences are nonlinear and are obtained by the manufacturers empirically. The input values of the table E2 corresponding to the influence of the temperature while these of the table E3 – for the relative humidity. The equivalent output voltages are multiplied and the obtained voltage signal in net labeled as N61871 is equal to the relative sensitivity.

3. ABM2/I – ABM expression part with two inputs and current output is used for transforming the voltage in net N61871 (or the relative sensitivity) into current. This part generate the output current specified by the expression:

$$I_{out} = \frac{V(IN1) - V(IN2)}{R_0 \cdot V(N61871)}. \tag{3}$$

4. RH – the value of the resistor is equal to the built-in heater resistance given in the datasheets [5].

5. S1– voltage-controlled switch is used for modeling the necessity of optimum temperature of the sensor surface. The switch turns off the sensor when the heater is not properly connected.

4. SIMULATION OF GAS MONITORING SYSTEM

The design approach for metal oxide gas sensors modeling described above is implemented for TGS2610 LP gas sensor [6]. For economical circuit design, a thermistor is incorporated to compensate temperature dependence. Figure 2 shows an example of a basic circuit for gas detection, including temperature compensation for variations caused by ambient temperature fluctuations. Typical values for the circuit components are as follows: EPCOS thermistor type K156 with $R_{therm} = 10$ kΩ (25°C) and $B = 3400$; $R_1 = 12$ kΩ; $R_2 = 430$ Ω; $R_3 = 2.2$ kΩ; $R_4 = 4.3$ kΩ.

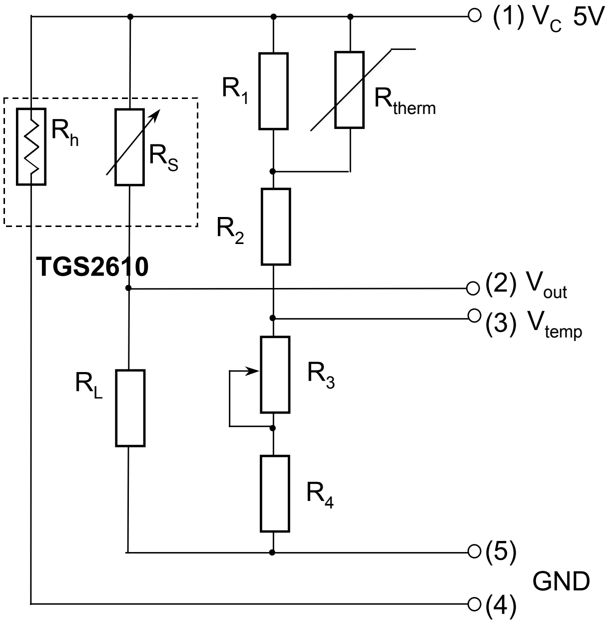

Fig. 2. Basic circuit for gas detection

The values for components related to temperature compensation should be chosen so that V_{temp} is one-half of the V_c value at standard temperature (25°C).

To optimize resolution of the output signal at the desired alarming concentration, it is necessary to adjust the resistance of the load resistor (R_L). It is recommended that R_L be selected at a value, which is equal to the sensor's resistance at the alarming concentration. Since the ID number corresponding to sensor resistance in iso-butane gas is indicated on the sensor cap, the load resistor value $R_L = 1514$ Ω is selected according to [6]. By using the recommended R_L, the V_{out} value at the alarming point typically will be 2.5V, which is equal to half of the circuit voltage (V_c).

Fig. 4 illustrates the simulation results of the sensor system from fig. 2, using the PSpice simulator. The results simulate behavior of the sensor system if the iso-butane gas concentration is changed from 300 ppm to 10 000 ppm. The monitoring system is designed for alarming in a typical set point at 10% LEL or for 1800 ppm iso-butane concentration. The simulation results of temperature curves of the voltages V_{temp} and

V_{out} are shown on fig. 5. It can be seen that the two temperature dependencies are approximate identical and the compensation is properly done.

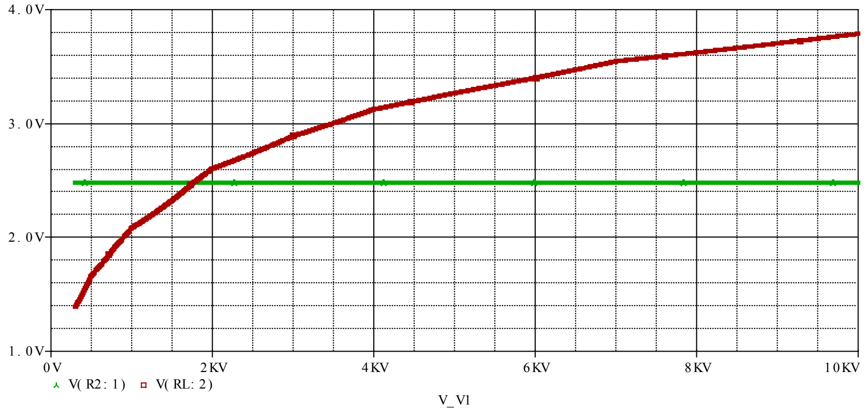

Fig. 4. The results for simulation of gas concentration

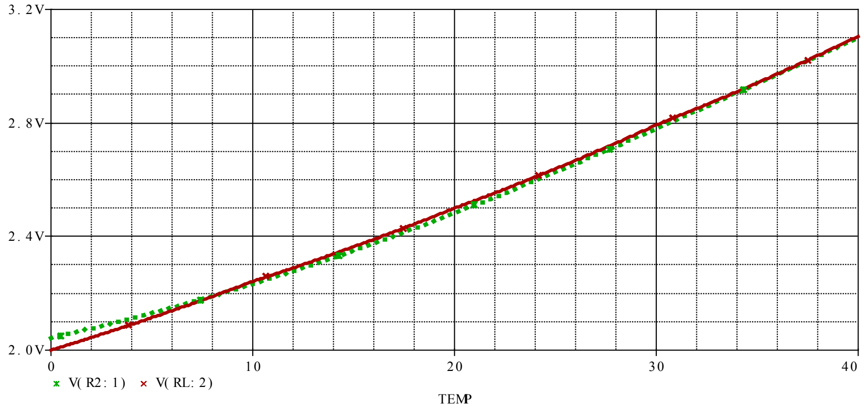

Fig. 5 The results for temperature simulation

5. CONCLUSION

In this paper a PSpice behavioral model of metal oxide resistive gas sensors is presented. The ABM of TGS2610 LP gas sensor is developed and used to design and simulate the gas monitoring system. The simulation results demonstrate a good agreement between the designed model and the sensor's datasheet characteristics. It can be seen also that the used temperature compensation is well done. The proposed modeling approach is suitable to predict behavior of other type of Taguchi gas sensors and for variety types of gases.

6. REFERENCES

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