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Principles and interfacing of resistive gas sensors

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Abstract

This work presents a sequence to introduce resistive gas sensors in the classroom. It explains the physical principle of the metal oxide semiconductor sensors and exemplifies its real interfacing through the sensor model MQ-2. Besides, it also presents the design of two electronic systems to indicate the level of alcohol concentration in the air, which are relatively simple and aim to motivate students through practical activities.

1. Introduction

This work focuses on the sensing of gases, which is a subject with large potential for science education [1, 2]. Gas sensing is an activity with applications in different areas. There are several industrial processes that require precise amounts of gases in industrial segments, such as food, beverage, energy, petrochemical, and pharmaceutical areas. Besides, industries can also generate undesirable polluting gases, whose monitoring is fundamental for the environment and health protection. Residences can use butane as cooking fuel and methane as heating fuel, which are flammable gases and monitoring them can avoid fires. In short, gases are present in our daily lives more than we can imagine.

This is a subject that involves many concepts, and therefore it requires an adequate educational strategy and a minimal technical formalism degree to ensure concrete learning. In fact, there are several popular works that show the use of sensors of gases in the Internet, but usually they do not clearly detail either the physical sensor principle nor specificities about its interfacing, which becomes a problem for effective educational approaches and may induce a false sense of knowledge.

The context above has motivated this work, which presents this subject through a logical sequence that can make more effective its analysis in the classroom. Its strategy is to divide this subject teaching in the sequence:

1. The physical analysis of metal oxide semiconductor (MOS) sensors, whose electrical resistance varies according to the gas concentration.
2. The sensor interfacing to compose a voltage divider circuit to provide an output voltage proportional to the gas concentration.
3. The designs of electronic sensing systems to indicate the level of gas concentration.

2. The sensor principle of operation

This work uses the sensor of gases model MQ-2, which is a sensor type MOS and has an operational principle based on the variation of its internal electrical resistance according to the gas concentration around it. In fact, there are different types of gas sensors, but the type of MOS is interesting for educational approaches because of its low cost, interesting operational principles and simplicity of interfacing [3–5].

Metal oxides are chemical compounds that contain one or more oxygen atoms and a metal,

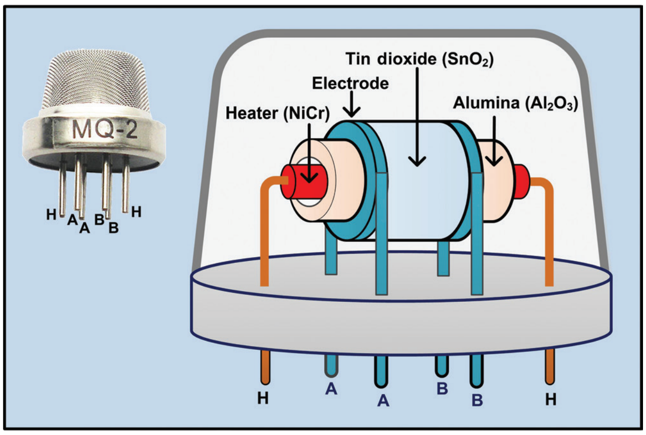

Figure 1. The MOS sensor structure.

several of which present semiconducting properties and therefore they are referred to as MOS. These compounds present a natural variation of their electrical characteristics in the presence of some specific gases, and therefore become appropriated for the design of gas sensors.

Figure 1 exemplifies the MQ-2 structure, which is typical for all sensor type MOS. Tin dioxide (SnO_2) works as the sensing element, which presents a high electrical resistance (Rs) in the absence of gases (clean air) and a low resistance in their presence [4].

SnO_2 is an n-type semiconductor that absorbs the air oxygen on its surface, and it attracts SnO_2 donor electrons. Consequently, Rs increases in the clean air and it encumbers the current flow through it. However, the level of absorbed oxygen decreases in the presence of gases, and it releases the electrons to allow a current flow through SnO_2 [3–6]. In fact, during the crystal growth, oxygen vacancies are created in the SnO_2 crystal lattice to compose it in the non-stoichiometric form SnO_X, where $1 < x < 2$, which facilitates the easy adsorption of oxygen at its surface and the operation as a sensor [8–10].

Tin dioxide requires a few hundred degrees Celsius to work as a sensing element [3], and so the manufacturers sinter it on a ceramic tube of aluminium oxide (Al_2O_3) that has an adequate thermal conductivity and allows a more uniform heat transfer from a nickel–chromium (NiCr) resistor placed inside it. The resistor heats naturally under an applied voltage due to the Joule heating, and therefore it provides the required heat for the tin dioxide.

Note that detailed studies on this sensor include advanced physical and chemical concepts. However, its basic principles can be easily understood and it may encourage students for other future gradual studies.

3. The sensor interfacing

The NiCr (heater) and tin dioxide (sensing element) operate as electrical resistive elements, which are schematically represented by traditional resistors that in this work are called RH and Rs, respectively.

Figure 2 shows the basic schematic for this sensor interfacing. It connects Rs in series with an external resistor (RL), and these two resistors compose a circuit called a voltage divider [3, 6] that increases Vo when Rs decrease in the presence of gas. In other words, Vo increases when the gas concentration increases, and it decreases when the gas concentration decreases.

Equation (1) expresses the Vo value. Note that RL has a fixed value, and therefore Vo depends on the Rs variation.

$$\mathrm{Vo} = \left(\frac{\mathrm{Vcc}}{\mathrm{Rs} + \mathrm{RL}}\right) \mathrm{RL}. \qquad (1)$$

Theoretically, Rs should have an exact constant value under a fixed concentration of gases. However, in practical approaches, it does not occur and Rs can vary according to each sensor piece, temperature, and humidity.

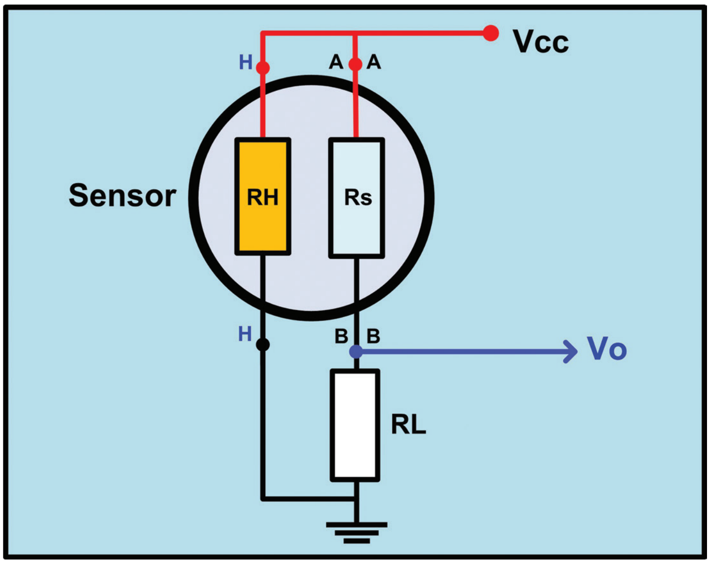

Figure 2. The sensor interfacing as a voltage divider.

To solve this problem, the sensor manufacturers measure the RS value under precise and controlled conditions in their laboratories, using a fixed concentration of gas, temperature and humidity. This specific value of Rs is so called R0 and becomes a referential. Based on this context, manufactures do not express the absolute value of Rs in their datasheets, but use its ratio with R0, which also makes the comparison between different sensors easier. Figure 3 shows the manufacturer's graph [11] for the relation between the alcohol concentration and the ratio (RS/R0). Note that, in the albescence of gases (clean air), the ratio Rs/R0 assumes a fixed value at 9.8 (blue line), which becomes another referential.

The first operational step for this sensor utilization is the Rs verification in the absence of gases (clean air), which will be a referential for future measurements. This operation measures Vo in clean air and computes Rs as:

$$\mathrm{Rs} = \left(\frac{\mathrm{Vcc\,RL}}{\mathrm{Vo}}\right) - \mathrm{RL}. \qquad (2)$$

In this work, the Rs value in the clean air (absence of gas) will be referred to as Rsc to allow easier identification. The presented first step must be performed whenever the sensor is turned on, but after it, the system can perform countless measurements.

For each effective measurement after the first step, Vo is measured in the presence of gases and the corresponding Rs value is computed. Next, the resistive relation (Nr) without gas and with gas is computed as:

$$\mathrm{Nr} = \frac{\mathrm{Rsc}/\mathrm{R0}}{\mathrm{Rs}/R0} = \frac{\mathrm{Rsc}}{\mathrm{Rs}}. \qquad (3)$$

It means that the ratio (Rs/R0) at clean air, fixed at 9.8, decreased Nr times in the presence of gas, and therefore (Rs/R0) in the presence of gas is computed as:

$$(\mathrm{Rs}/\mathrm{R0}) = \frac{9.8}{Nr}. \qquad (4)$$

Finally, the computed value of (Rs/R0) with equation (4) intercepts the concentration of gas (ppm) through the red line in figure 3.

For example, for RL fixed at 10 KΩ and Vcc at 5.0 V. If Vo was measured at 1.3 V in the clean air, so Rsc would be:

$$c = \left(\frac{5\,\mathrm{V} * 10\,\mathrm{K}\Omega}{1.3\,\mathrm{V}}\right) - 10\,\mathrm{k}\Omega\Omega$$

$$\mathrm{Rsc} = 28.5\,\mathrm{K}\Omega.$$

Supposing a later measurement of gases, where Vo is measured at 4.0 V, so:

$$\mathrm{RS} = \left(\frac{5\,\mathrm{V} * 10\,\mathrm{K}}{4\,\mathrm{V}}\right) - 10\,\mathrm{k}\Omega$$

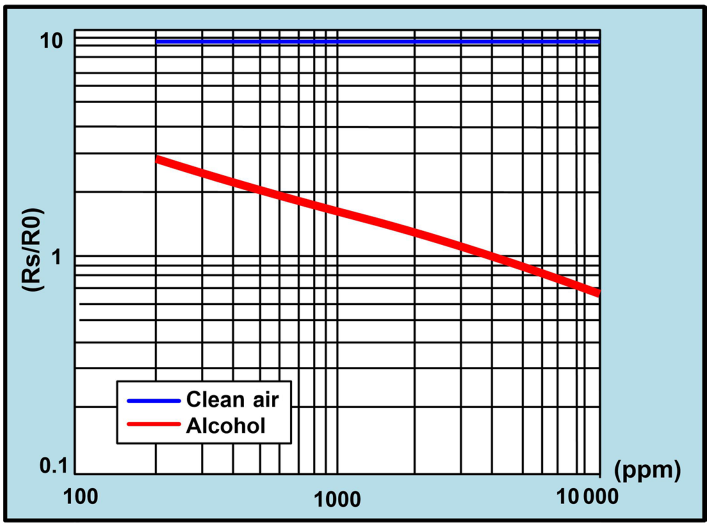

Figure 3. The MQ-2 alcohol concentration graph.

$$\mathrm{Rs} = 2.5\,\mathrm{K}\Omega$$

In this case, Nr is:

$$\mathrm{Nr} = \frac{28.5\,\mathrm{K}\Omega}{2.5\,\mathrm{K}\Omega} = 11.4.$$

Therefore, the ratio (RS/RO) in the presence of this alcohol concentration would be:

$$(\mathrm{Rs}/\mathrm{R0}) = \frac{9.8}{11.4} = 0.86.$$

Finally, the Rs/R0 value at 0.86 is analyzed in the red line in figure 3, where it intercepts the value of 5000 ppm that is the final result.

This work focuses on the measurement of the alcohol concentration in the air because it is a substance that is easy to get and manipulate. However, MQ-2 can sense alcohol, propane, hydrogen, LPG, and smoke.

In fact, MQ-2 is only one sensor of a large line that includes several other models. For example, the sensor MQ-3 can sense alcohol, LPG, and benzene. Both can sense alcohol but MQ-2 operates in a range from 100 to 10 000 ppm, while MQ-3 operates in a range from 0.1 to 10 ppm and therefore is indicated for operations in environments with a smaller concentration of alcohol.

Despite the MOS technology advantages, its use requires some observations:

1. Usually this sensor can detect different gases, but it cannot indicate what the surrounding gas is. It represents a problem of *selectivity*, which may not be critical as long as the user knows what gas is in the environment.
2. The ambient temperature and humidity directly influence the sensor. Figure 4 shows the MQ-2 manufacturer's graph [11], which shows the typical influence values. It means that a more accurate gas measurement requires additional temperature and humidity measurements and the corresponding corrections of the gas measurement. However, it is usually neglected for a simple sensor demonstration.
3. The sensing element requires a heating time to ensure an adequate operation. The MQ line reaches the ideal temperature of operation only at least 48 h after its powering. However, they reach a minimum acceptable operational temperature at about two minutes [11].

Note that this type of sensor is a consolidated technology that ensures more advantages than disadvantages, and therefore it has been widely used in commercial systems and also motivated scientific researches.

Unfortunately, this sensor has a high energy consumption to be powered by batteries, whose lifetime (Lt) is computed as:

$$\mathrm{Lt} = \frac{\mathrm{Bc}}{\mathrm{Ic}} \tag{5}$$

where Bc is the battery capacity, expressed as Ah (ampere hour) and Ic is the powered circuit current.

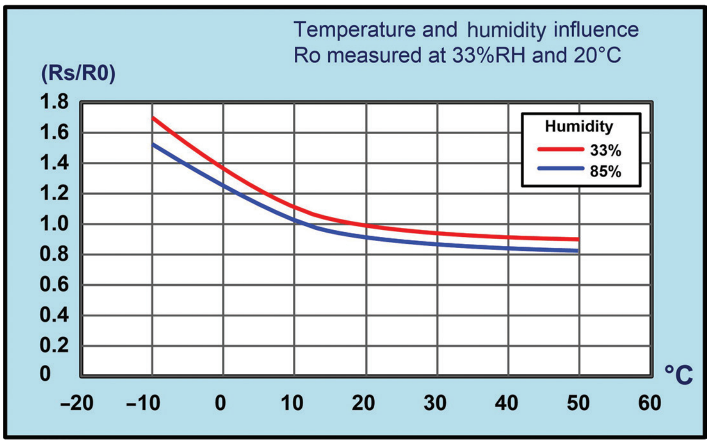

Figure 4. MQ-2 temperature and humidity influence.

The heating resistor is the main factor responsible for this sensor consumption. It has a value of 33Ω with a possible variation of ±3% [11], and therefore its current when powered with 5 V can reach up to 156 mA. In this case, a battery with a capacity of 2800 mAh could power the sensor by only 18 h. It may be a problem for the design of portable devices with this sensor, but it can be neglected for indoor operations powered by the electrical grid. This maximum sensor power consumption is 0.78 W (5 V $*$ 156 mA), which may be high for a battery, but is very low for the electrical grid.

4. The sensing systems

This section presents two measurement systems with the MQ-2 sensor. The first uses an Arduino board and the other does not, which is an example that many measurement systems can be designed with or without a processor. This observation may be an opportunity to present in the classroom the concept of 'intelligent instruments', which basically define instruments that include a data processing ability.

The intelligent instruments present advantages as a reconfiguration by software that may require little or no hardware complements, immediate mathematical data processing, and connectivity with telemetry or internet systems. However, in spite of the intelligent instrument advantages, the 'nonintelligent' or traditional electronic instruments compose an important base for the electronic instrumentation area. Therefore, they remain important for several applications and should not be despised.

5.1. The measurement system with an Arduino

Figure 5 exemplifies the experiment structure, where a plastic or wood base fixes the sensor. The teacher can approximate and stand the base back to a container with alcohol to expose the sensor to different concentrations.

Remember that alcohol is flammable and therefore this experiment requires special attention with regards to safety aspects. In this experiment, the sensor is hot and connected to electricity, and therefore must not have direct contact with the alcohol liquid.

For a more realistic exemplification, figure 6 shows a way to connect the sensor with RL fixed at 10 KΩ and wires for powering with 5 V from the Arduino board. This work used a connection similar to figure 6, but there are other different possibilities, and the use of a small printed circuit board can allow a more reliable connection.

Figure 7 shows the program that runs in the Arduino board.

The program does not perform the result correction according to the environment temperature and humidity, which would require two other sensors. It means that this measurement may present a small margin of error, which is usually neglected for simple demonstrations. However, to mitigate the problem of sensor result variations,

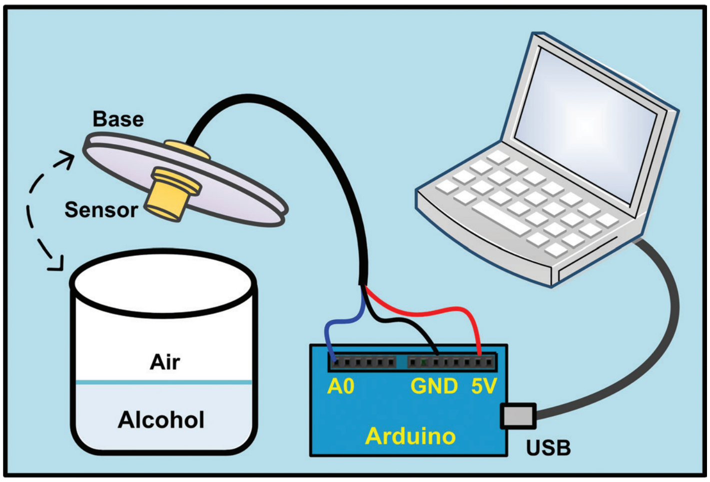

Figure 5. Experiment structure.

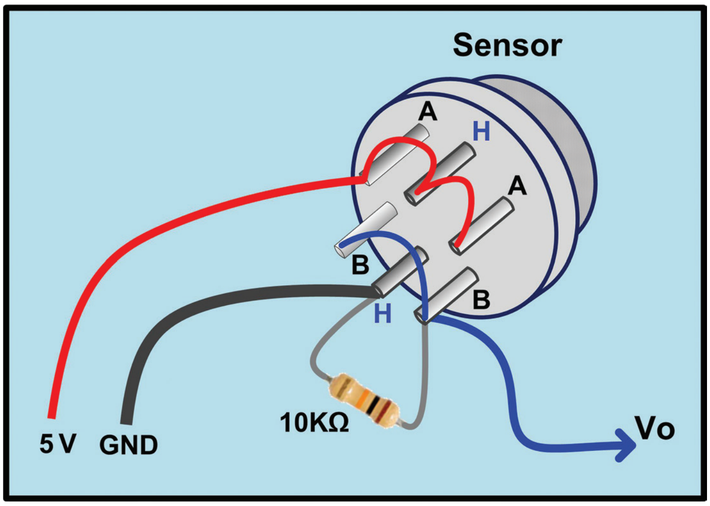

Figure 6. Example of sensor connection.

this program reports the measurement results only in the fixed ranges shown in table 1.

Figure 8 shows the result of an experiment whose alcohol concentration ranges were numbered according to table 1. It used the structure in figure 5 and the program in figure 7. In this experiment, 100 ml of alcohol was put inside a small cup with an opening diameter of 6.5 cm and a height of 7.5 cm. The cup was initially opened, and the sensing took about 50 s to stabilize after the sensor base closed its opening. This time occurs because of the influence of the sensor response time and the alcohol concentration stabilization in the space of air between the liquid alcohol and the sensor base.

5.2. The measurement system without Arduino boards

Figure 9 shows another way to interface this sensor, but without an Arduino board. It is the schematic of an alarm that turns on an LED when the gas concentration is higher than a specific value.

This circuit understanding does not require software knowledge and its operation is simple and intuitive, even for students with little background in electronics. Therefore, it may be a way to start and motivate students in the electronic instrumentation area.

The circuit is based on an operational amplifier model LM324 configured as a non-inverting

```
// Arduino Program – Alcohol Cocentration with the MQ-2 Sensor

#define RL  10000   //RL resistor (voltage divider) fixed at 10K
float Vo, RSair, RsR0, Rs, N;
int x, cont;

void setup(void)
{
 Serial.begin(9600); //Initialize the serial communication

 Serial.println("Please, wait 2 minutes");
 Serial.println("The sensor is heating ...");
 delay(120000);  //Delay two minutes

 Vo=0; //Measure Vo as the mean of thirty values
 for (x=1; x<=30; x++) { Vo=Vo+analogRead(0);}
 Vo=Vo/30;
 Vo=Vo*0.004883;
 RSair = (5-Vo)/(Vo/RL);  //Compute RSair (Rs in the clearn air)
 cont=0;
 }

void loop(void)
{
  Vo=0; //Measure Vo as the mean of thirty values
  for (x=1; x<=30; x++) { Vo=Vo+analogRead(0); }
  Vo=Vo/30;
  Vo=Vo*0.004883;

  Rs = (5-Vo)/(Vo/RL); //Compute RS
  N=RSair/Rs;            //Compute N
  RsR0=9.8/N;            //Compute RsR0 in the gas presence

  cont=cont+1;      //Print the number of each measurement
  Serial.print("Measurement: "); Serial.print(cont); Serial.print(" - ");

  //Verify and print the gas concentration range.
  if (RsR0>=2.9)        {Serial.println("Range 1: 0...200 ppm");}
  else if (RsR0>=2.5) {Serial.println("Range 2: 201...300 ppm");}
  else if (RsR0>=2.1) {Serial.println("Range 3: 301...500 ppm");}
  else if (RsR0>=1.7) {Serial.println("Range 4: 501...1000 ppm");}
  else if (RsR0>=0.9) {Serial.println("Range 5: 1001...5000 ppm");}
      else          {Serial.println("Range 6: 5001...10000 ppm");}
  delay(1000);      //Wait 1 seconds
}
```

Figure 7. The Arduino program.

comparator circuit, which compares Vo and Vref and presents an operation summarized as [7]:

- If Vo > Vref then Vc is high and turns on the LED.
- If Vo < Verf then Vc is low and turns off the LED.

The Vref value adjustment follows the sequence:

1. Turn on the power source and wait at least two minutes for the sensor heating.
2. Turn potentiometer until Vref reaches maximum value at about 5.0 V, which turns

Table 1. Ranges of alcohol concentration.

Range	Alcohol concentration (ppm)
1	0–200
2	201–300
3	301–500
4	501–1000
5	1001–5000
6	5001–10 000

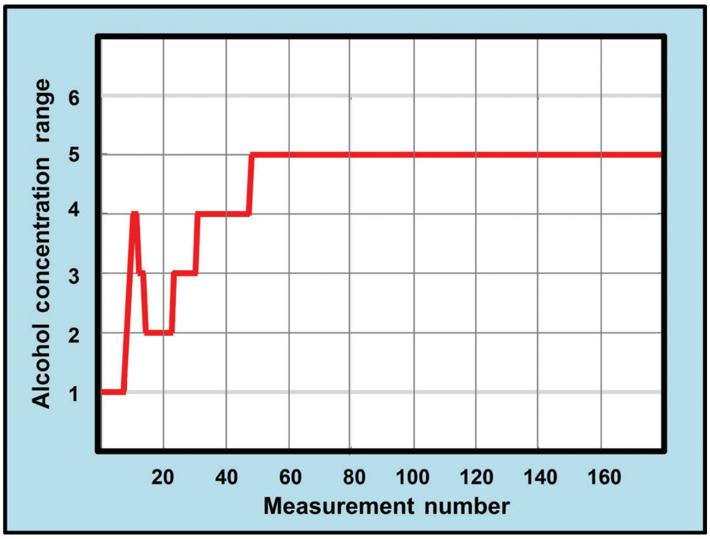

Figure 8. Real measurement results.

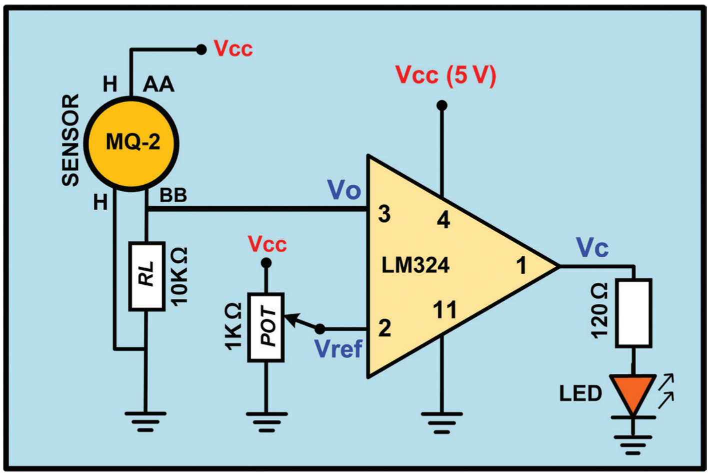

Figure 9. Alarm for gas level detection.

off the LED.

3. Put the sensor in an environment with a specific concentration of gas.
4. Decrease Vref, turning the potentiometer until the LED turns off. When it occurs, Vref reaches the reference value.

After the adjustment, the circuit will turn on the LED every time the gas concentration is greater than the value used in the setting. However, slight variations may occur because of the temperature and humidity influence, and even because of the measurement system precision.

5. Conclusion

This work has shown the basic physical principles of the sensor of gas type MOS and proved they allow practical approaches in educational laboratories through the design of simple electronic measurement systems with and without processing.

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References

[1] Cortón E *et al* 2000 Potentiometric determination of CO_2 concentration in the gaseous phase: applications in different laboratory activities *J. Chem. Educ.* **77** 1188–90
[2] Pino H *et al* 2019 Measuring CO_2 with an Arduino: creating a low-cost, pocket-sized device with flexible applications that yields benefits for students and schools *J. Chem. Educ.* **96** 377–81
[3] Miller T A *et al* 2006 Nanostructured tin dioxide materials for gas sensor applications *Functional Nanomaterials* ed K Geckeler and E Rosenberg (Valencia, CA: American Scientific Publishers) ch 30
[4] Thompson J E 2016 Crowd-sourced air quality studies: a review of the literature & portable sensors *Trends Environ. Anal. Chem.* **11** 23–34
[5] Dey A 2018 Semiconductor metal oxide gas sensors: a review *Mater. Sci. Eng.* B **229** 206–17
[6] Watson J *et al* 1993 The tin dioxide gas sensor *Meas. Sci. Technol.* **4** 711–9
[7] Perea Martins J E M 2018 Automation experiments in physics laboratories *Phys. Educ.* **53** 055009
[8] Kaur M, Asawal D K and Yakhmi J V 2007 Cheminresistors gas sensors: material, mechanisms and fabrication *Science and Technology of Chemiresistor Gas Sensors* ed D K Aswal and S K Gupta (New York: Nova Science)
[9] Eranna G 2012 *Metal Oxide Nanostructures as Gas Sensing Devices* (Boca Raton, FL: CRC Press)
[10] Deng Y 2019 *Semiconducting Metal Oxides for Gas Sensing* (Berlin: Springer)
[11] Hanwei Electronics 2019 *Technical Data MQ-2 Gas Sensor* (Zhengzhou, Henan: Hanwei Electronics)

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