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Conclusion of the Operating Points of a Gas Sensor Set When Exposed to Domestic Gas

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Abstract:

This study analyzes the behavior of a set of gas sensors from the French company [FIGARO/Taguchi Gas Sensors] (TGS26-series) when exposed to domestic gas under different heating voltages, with the objective of determining the optimal operating conditions. The sensors were interfaced with an Arduino board to record readings, and the collected data were processed and analyzed using MATLAB software to evaluate performance characteristics. Findings indicate that a heating voltage of VH = 5.5V yields the most favorable results, demonstrating the fastest response time and the lowest stability resistance. These outcomes highlight the optimal operating voltage for the selected sensor set. The study contributes to enhancing sensor efficiency in practical scenarios, particularly in detecting household gas leaks. This, in turn, supports efforts to improve home safety and mitigate risks associated with gas exposure. Notably, the research offers a detailed performance assessment and establishes clear parameters for optimal sensor operation, thus reinforcing both its scientific rigor and applied relevance.

Keywords: *Resistance; Sensor Circuit; Heating Voltage; MATLAB; Domestic Gas.*

استنتاج نقاط عمل شبكة حساسات غازية لدى تعرضها للغاز المنزلي

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ملخص:

تحلل هذه الدراسة سلوك مجموعة من حساسات الغازات التابعة للشركة الفرنسية [FIGARO/Taguchi Gas Sensors] (سلسلة TGS26) عند تعرضها للغاز المنزلي تحت جهد تسخين متغير، بهدف تحديد ظروف التشغيل المثلى. تم توصيل الحساسات بلوحة أردوينو لتسجيل القراءات، وتمت معالجة البيانات الناتجة وتحليلها باستخدام برنامج MATLAB لتقييم مؤشرات الأداء. أظهرت النتائج أن جهد التسخين VH = 5.5 فولت يُعد الأمثل، حيث سجّل أفضل زمن استجابة وأدنى مقاومة استقرار. وتؤكد هذه النتائج على الجهد التشغيلي الأمثل لمجموعة الحساسات المدروسة. تُسهم هذه الدراسة في تحسين كفاءة الحساسات في التطبيقات العملية، لا سيما في الكشف عن تسربات الغاز المنزلي، مما يعزز من مستوى الأمان المنزلي ويقلل من المخاطر المرتبطة بالتعرض للغاز. وتتميز الدراسة بتقديم تقييم دقيق لأداء الحساسات وتحديد المعايير المثلى للتشغيل، مما يعزز من قيمتها العلمية والتطبيقية.

الكلمات المفتاحية: *مقاومة؛ دارة الحساس؛ جهد التسخين؛ الماتلاب؛ الغاز المنزلي.*

1. Introduction

As a result of the rapid development in all fields of life, especially in industrial, commercial and environmental applications, it was necessary to find new means to serve these applications, so sensors had an important role in this because of their many types, for example in industry, many companies replaced humans with sensors that shortened time and were more accurate in work, and for the environment, gas sensors had a clear distinction in identifying large numbers of vapors or gases within certain conditions, as they were used to detect possible leaks in pipes or in public places, or even in homes, so studies on gas sensors expanded.

Therefore, many researchers worked on this topic and reached conclusions that led to an increase in the number of applications for sensors, and the rapid development and progress made it very easy to deal with them either individually or by connecting them to circuits that enable us to change their operating conditions.

It is known that there are many gases that are dangerous to human life, such as gases that are used in homes as well as industrial facilities, as they are considered toxic and highly flammable, which we must detect in the easiest and least expensive ways.

To minimize this risk, either gas sensors can be manufactured that can detect these gases or develop old sensors, and the operating conditions of sensors previously manufactured by companies can be modified.

There are many studies about this field:

- Researcher Jiao et al. (2002) from China successfully developed a gas sensor made from $ZnGa_2O_4$ nanocrystals to study its response to several gases such as LPG, CO, C_2H_5OH, and CH_4. The researchers observed that the sensor's response to liquefied petroleum gas (LPG) at a concentration of 500 ppm was better compared to the other gases.
- Researcher Chen et al. (2017) from China successfully developed a gas sensor made of titanium dioxide (TiO_2) nanoparticles activated with palladium (Pd) particles at a concentration of 7.5 mol% to detect butane gas at a concentration of 3000 ppm. The researchers obtained a good response and a response time about 13 Sec, which is about 9 times higher than the sensor made of pure titanium nanoparticles.
- Researcher Rana et al. (2023) from India successfully developed a sensor to detect butane gas by adding a small amount of multi-walled carbon nanotubes (MWCNTs) and palladium to its base material, tin oxide. The researchers observed an improvement in the gas's sensitivity response at a concentration of 2000 ppm with an efficiency of 93% and a response time of 2 Sec, as well as a decrease in the operating temperature.
- Researchers Zegebreal et al. (2023) from Ethiopia highlighted on studies about introducing new elements to the sensor material during its manufacturing, such as hybrid conductive polymers and nanomaterials of metal oxides, to improve its performance at room temperature. These studies showed excellent performance in detecting various gases and vapors, concluding that one of the most important elements for improving the response of any sensor is the chemical composition of its material.
- Researcher Chakraborty et al. (2006) from India were able to develop gas sensor using iron-doped tin oxide to detect methane and butane gases at an activation temperature of 350 ^{0}C, Palladium was added as a catalyst to the sensor material, and the researchers noticed an improvement in the response to many gases due to modifying its chemical composition and adding catalytic elements.
- Researcher Liu et al. (2015) from China have developed a gas sensor using tungsten-doped titanium dioxide to detect butane, the sensors showed an improvement in response from (6 to

17.8) in 2 Sec and a reactivation time of 12Sec when exposed to 3000 ppm of gas, when doped with 5% tungsten.

- Researcher Balamurugan et al. (2012) from India studied the behavior of a gas sensor made of $CrNbO_4$ nanocomposite towards several gases (LPG, ethanol, ammonia) in terms of working temperature, gas concentration and response time, where the researchers noticed that the best response was for LPG with 0.87, while for ethanol 0.66 and for ammonia 0.49.
- Researcher Javed et al. (2018) from the United States used a set of gas sensor to measure the concentration of gas in unknown gaseous mixtures similar to diesel engine exhaust, the researchers noted that the accuracy of the results will be greater when either reducing the number of sensors or decreasing the number of gases in the mixture.
- Researcher Wang et al. (2023) from China were able to synthesize hollow cubes of indium oxide using different amounts of urea, the best cube was In2O3 (In2O3-5) with a molar ratio of (InC13:CH4N2O) of 1:5 where response 84.1 for it at an operating temperature of 180 ^{0}C and a response and recovery time of 9 Sec, this sensor also demonstrated excellent selectivity towards propane compared to carbon monoxide, ethylene, ethanol, hydrogen, and hydrogen sulfide.
- Researcher Patil et al. (2012) from India studied the effect of the sintering temperature used in the fabrication of gas sensor made of magnesium ferrite oxide to detect a range of gases (LPG, acetone, ethanol, ammonia), where it was found that there is a significant impact on the performance of these sensor, as it was observed that the maximum response to LPG at a concentration of 2000 ppm is 71% at a temperature of 698K.
- Researcher Bhargav et al. (2014) from India studied the sensitivity of gas sensor made of lanthanum iron oxide nanocomposite at low temperature 250 ^{0}C towards butane gas, the researchers observed that this material improved the response due to its effective catalytic nature towards butane oxidation.
- Researcher Shah et al. (2024) from France studied of a set of gas sensor from FIGARO [TGS2602, TGS2611-C00, TGS2611-E00) to detect methane gas in a landfill, the studies showed that the best sensitivity to methane gas among these sensors was TGS2611-C00.

2. Practical Part:

We chose a set of gas sensors from Figaro's TGS 26-- series, (2600, 2602, 2611, 2612, 2620, 2630). All of these sensors share the characteristic that their sensitive material is made from metal oxides and they have the same operating circuit as shown in Figure (1):

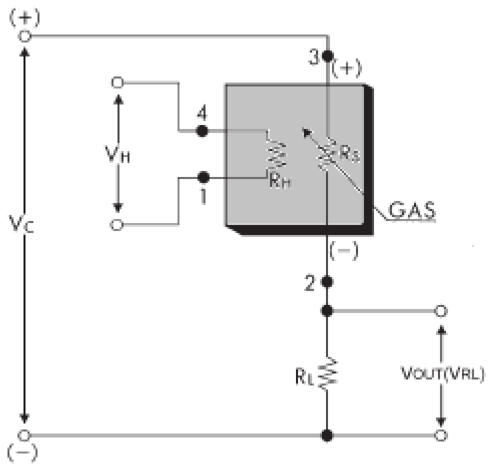

Figure (1): The electronic circuit of the Figaro TGS 26-- gas sensor

Each sensor circuit operates with a supply voltage (V_C = 5V) and a variable heating voltage (V_H), which influences its response characteristics**.** This voltage helps in heating (activating) the sensor layer that captures the target domestic gas (Propane and Butane). We used several values for this voltage ranging from (3V to 7V) in steps of 0.5V. The load resistance (R_L) is set to 0.5KΩ, while the sensor resistance (R_S) is determined using the following equation (1) Helli (2003), which will be calculated using the Arduino program.:

$$R_S = \frac{V_S}{(V_C - V_S)} * R_L \qquad (1)$$

The ease of operating with the Arduino board and the wide range of modifications that can be made to the circuits connected to it, and the ease of programming it to cover a large number of variables.

Since gas sensors are used to detect the types of surrounding gases, they are pre-calibrated, and their operating points are determined, such as (heating voltage V_H, stability resistance R_S, stabilization time t, sensitivity S, activation energy, dissipation power, etc.). Therefore, we connected our set of sensors to the Arduino board.

3. Material and Methods:

1. All sensor circuits were connected to the Arduino board and then to the computer, with (V_C, V_H, R_L) connected to the previously mentioned values.
2. The Fritzing program was used to create the basic model for this set's as shown (2).

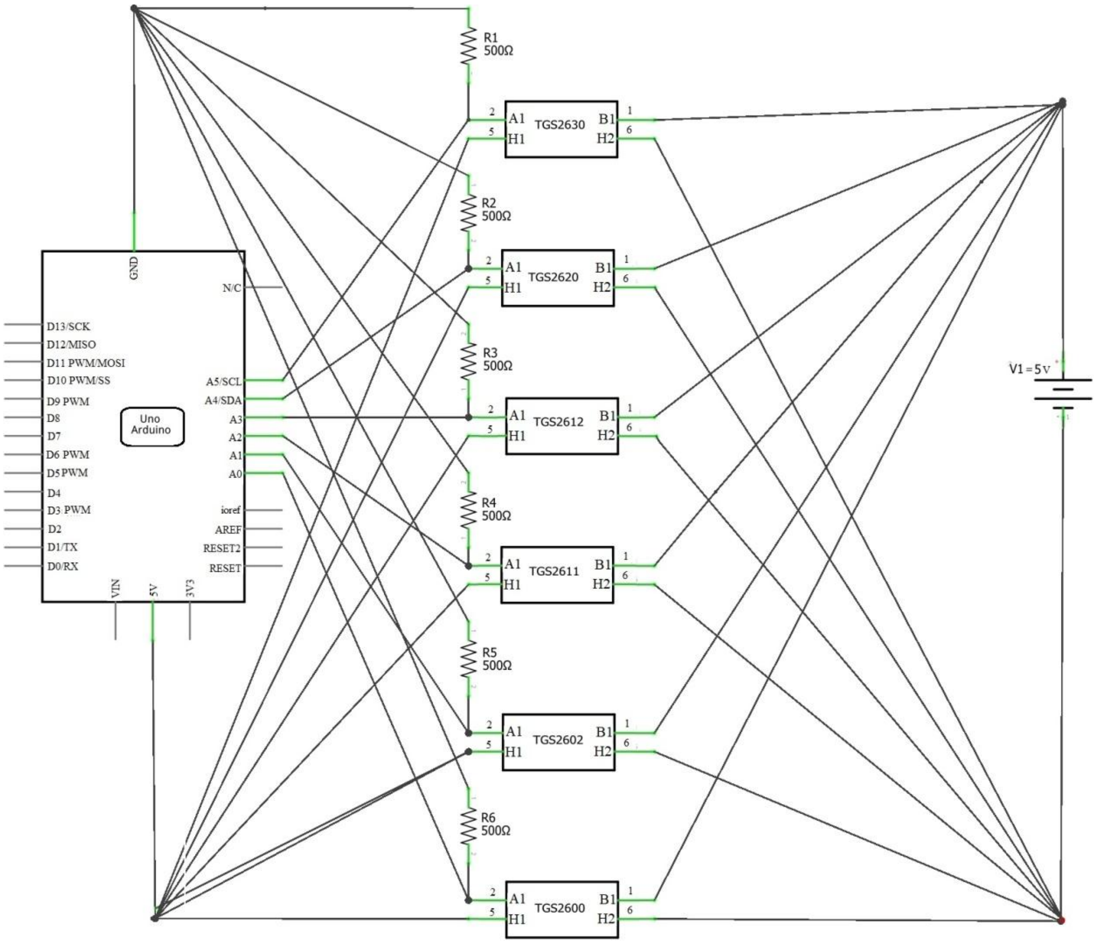

Figure (2) shows the sensor set with the Arduino board

3. The Arduino board was programmed to receive the readings generated by the outputs of sensors, and process the information, and prepare it.

We wrote the code for the set as follows:

```
// Set of sensors
const int sensorPins[6] = {A0, A1, A2, A3, A4, A5};
const float Vc = 5.0; // Circuit voltage
const float RL = 0.5; // Load resistance measured by K Ω
const float VL; // Output voltage
void setup() {
  Serial.begin(9600); //
}
void loop() {
  for (int i = 0; i < 6; i++) {
    int sensorValue = analogRead(sensorPins[i]);
float VL = sensorValue * (Vc / 1023.0);
    float Vs = Vc - VL;
if (Vs = = 0) {
    Serial.print("Error: Vs cannot be zero!");
        return;
      }
    float Rs = (Vs / (Vc - Vs)) * RL * 1000;
    Serial.print("Sensor ");
    Serial.print(i);
    Serial.print(" | VL: ");
    Serial.print(VL);
    Serial.print(" | Vs: ");
    Serial.print(Vs);
    Serial.print(" | Rs: ");
    Serial.print(Rs);
Serial.println();
  }
  delay(1000);
}
```

4. We exposed the sensor set to domestic gas (propane, butane) at a concentration (1000ppm), and then the study was repeated for several values of heating voltage (V_H). Each time, the results were recorded and then processed in MATLAB to plot the graphs, resulting in the following:

3.1 For TGS2600:

We exposed this sensor to the gas, we found that its resistance decreased until it reached stability. Table (1) shows the time it took for this sensor to reach a stable state and the stable resistance (R_S) at various heating voltage values, and the sensitivity was calculated from the relationship:

$$S = \frac{(R_0 - R_S)}{R_0}$$

Where R_0: is the initial sensor resistance (before the sensor is exposed to the gas)

Table (1): Shows the values of (t), (R_S), (R_0) and (S) at various heating voltage (V_H) values for the TGS2600 sensor.

V_H(v)	R_0 (K Ω)	R_S (K Ω)	$S = \frac{(R_0 - R_S)}{R_0}$	t (Sec)
3	182.440	30.442	0.83314	85
3.5	215.754	29.224	0.86455	81
4	252.737	27.513	0.89114	75
4.5	329.254	26.235	0.92032	73
5	404.630	24.152	0.940311	71
5.5	586.955	22.768	0.96121	72
6	326.603	22.454	0.93125	82
6.5	248.623	21.849	0.91212	105
7	229.304	21.323	0.90701	113

We note from the table that as the heating voltage increases, the time to reach the sensor's stable state decreases, except for the last three heating voltages where the time starts to increase. This is because the sensor loses some of its properties when exposed to a heating voltage higher than the recommended value, causing the sensor to be damaged. Therefore, it is not recommended to use these voltages when studying the sensor.

We also noticed a decrease in the sensor's resistance over time until reaching the stable state R_S, as it decreases with increasing heating voltage (the sensors, composed of metal oxides, exhibit semiconductor-like behavior, responding dynamically to variations in heating voltage), as we noticed the sensitivity increased with the heating voltage up to 5.5V, then decreased for the remaining voltage.

We calculated the average of these times at all heating voltages and we found that the sensor can detect the gas within a time of (t=84.1 Sec).

The data collected from the Arduino board was processed using MATLAB to obtain the following Figure (3) which shows the changes of R_S, S, t depending on the heating voltage:

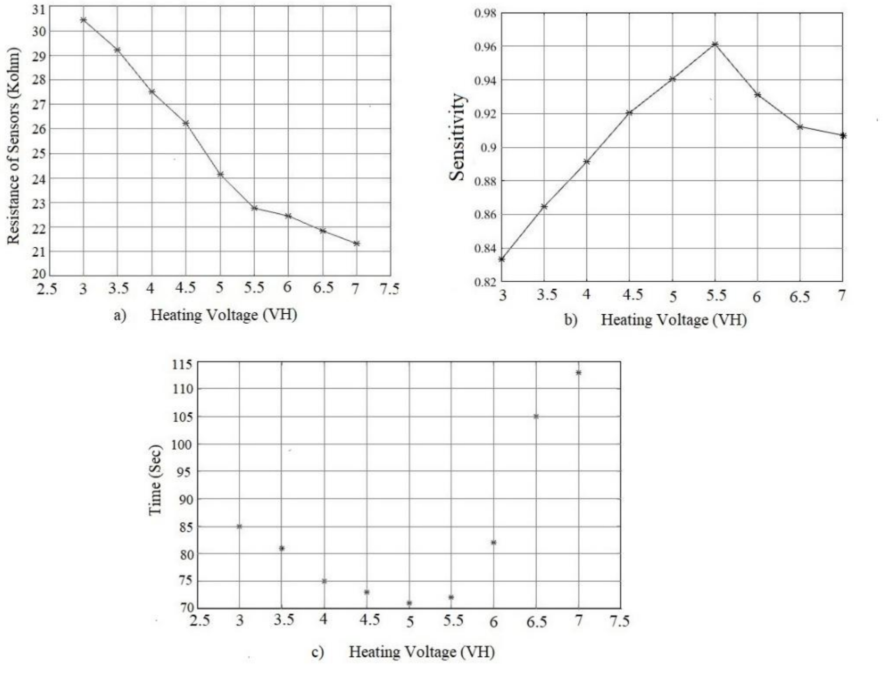

Figure (3): a): Shows the changes in resistance (R_S) with heating voltage (V_H) for the TGS2600 sensor b): Shows Changes in sensitivity (S) with heating voltage for the TGS2600 sensor c): Shows Changes in stabilization time with heating voltage for the TGS2600 sensor

3.2 For TGS2602:

At the same observation, we obtained Table (2), which shows the time taken by this sensor to reach stability, stable resistance (R_S), initial resistance (R_0) and sensitivity (S) at various heating voltage values.

Table (2): Shows the values of (t), (R_S), (R_0) and (S) at various heating voltage (V_H) values for the TGS2602 sensor.

V_H(v)	R_0 (K Ω)	R_S (K Ω)	S	t (Sec)
3	225.705	32.725	0.85501	118
3.5	230.383	32.021	0.86101	112
4	240.600	31.242	0.87015	106
4.5	275.814	29.024	0.89477	101
5	307.402	27.285	0.91124	95
5.5	404.124	26.454	0.93454	94
6	325.215	25.331	0.92211	103
6.5	253.185	24.759	0.90221	114
7	205.936	24.422	0.88141	138

Similarly, for the last three voltages of this sensor, the stabilization time increased and the sensitivity decreased as the heating voltage increased. We also calculated the average of these times at all heating voltages and found that this sensor can detect gas within a time of (t=109 Sec).

The following Figure (4) shows the changes of R_S, S, t depending on the heating voltage:

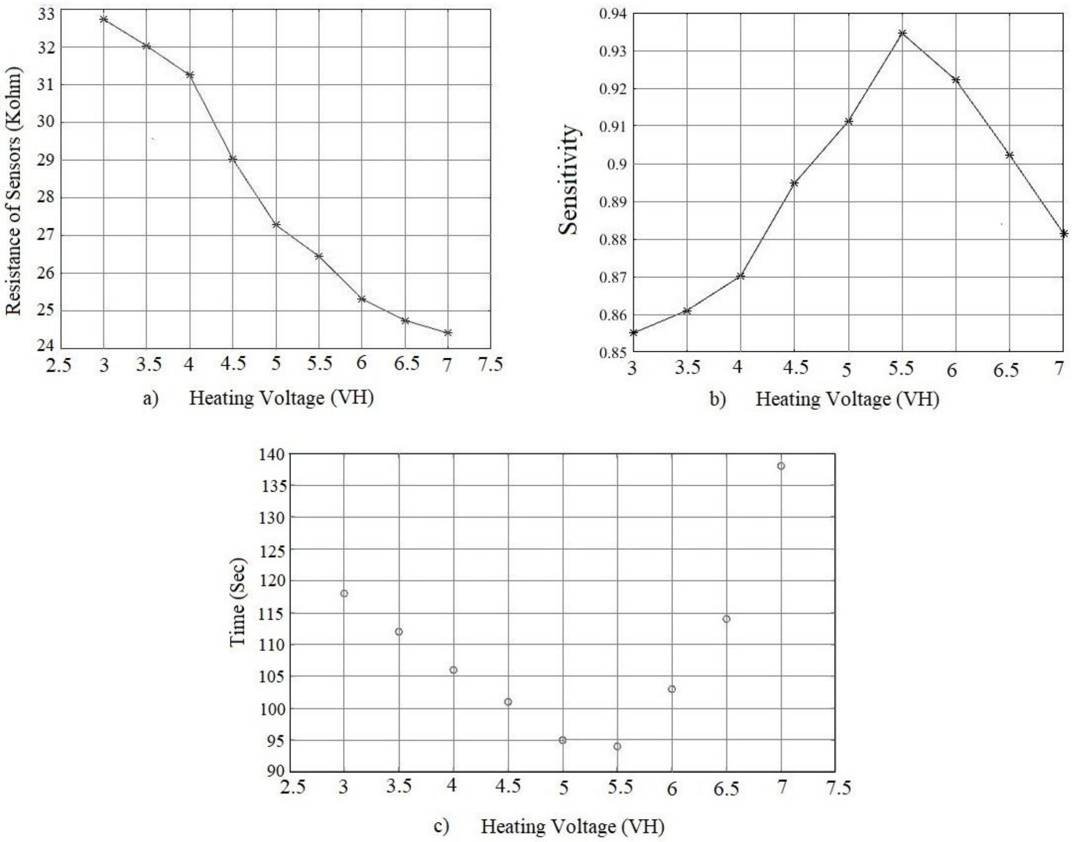

Figure (4): a): Shows the changes in resistance (R_S) with heating voltage (V_H) for the TGS2602 sensor b): Shows Changes in sensitivity (S) with heating voltage for the TGS2602 sensor c): Shows Changes in stabilization time with heating voltage for the TGS2602 sensor.

3.3 For TGS2611:

Similarly, we obtained Table (3), which shows the time taken by this sensor to reach stability, stable resistance (R_S), initial resistance (R_0) and sensitivity (S) at various heating voltage values.

Table (3): Shows the values of (t), (R_S), (R_0) and (S) at various heating voltage (V_H) values for the TGS2611 sensor.

V_H(v)	R_0 (K Ω)	R_S (K Ω)	S	t (Sec)
3	46.900	6.038	0.87126	97
3.5	50.833	5.581	0.89021	93
4	57.846	4.943	0.91455	85
4.5	63.243	4.224	0.93321	72
5	64.552	3.214	0.950211	70
5.5	115.158	2.978	0.97414	71
6	49.020	2.854	0.94178	84
6.5	39.296	2.702	0.93124	91
7	33.543	2.611	0.92216	97

Also, for the last three voltages of this sensor, the stabilization time increased and the sensitivity decreased as the heating voltage increased. We also calculated the average of these times at all heating voltages and found that this sensor can detect gas within a time of (t=84.4 Sec).

The following Figure (5) shows the changes of R_S, S, t depending on the heating voltage:

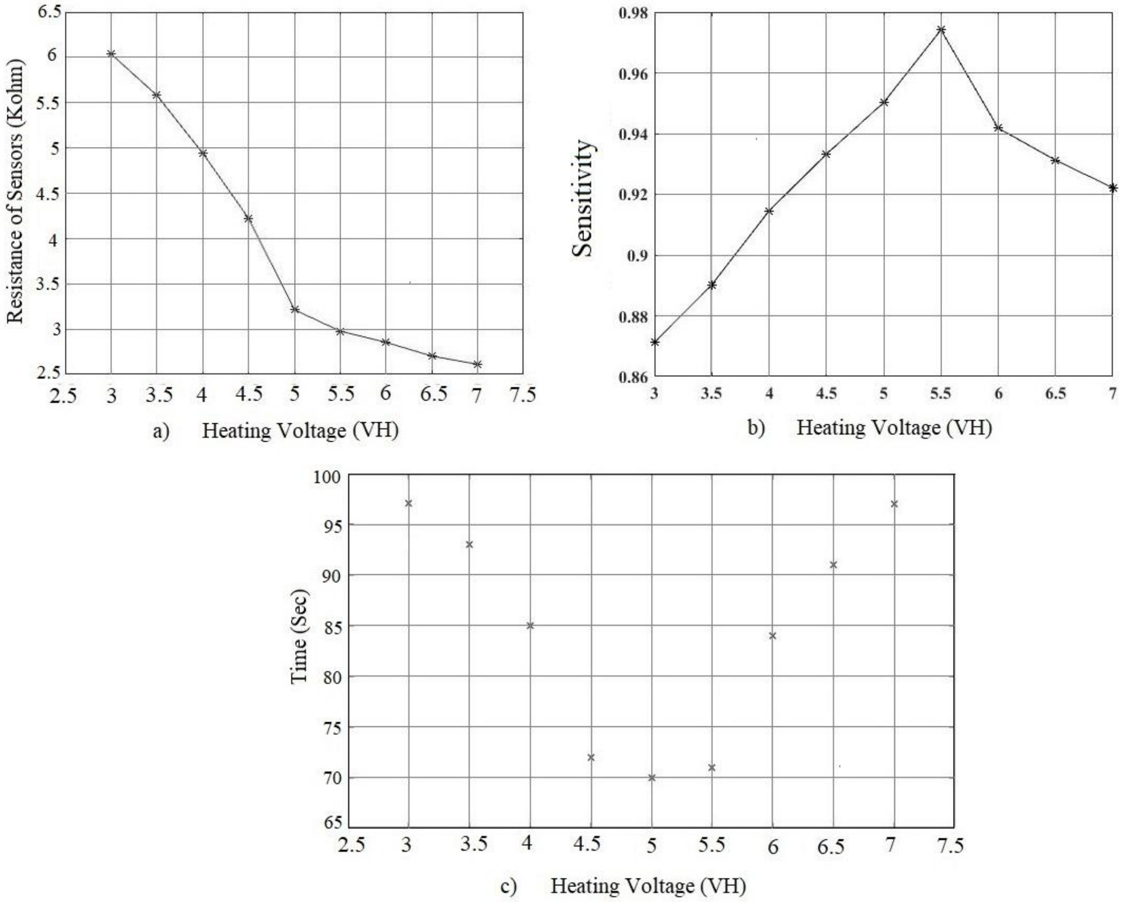

Figure (5): a): Shows the changes in resistance (R_S) with heating voltage (V_H) for the TGS2611 sensor b): Shows Changes in sensitivity (S) with heating voltage for the TGS2611 sensor c): Shows Changes in stabilization time with heating voltage for the TGS2611 sensor.

3.4 For TGS2612:

Table (4) shows the time taken by this sensor to reach stability, stable resistance (R_S), initial resistance (R_0) and sensitivity (S) at various heating voltage values.

Table (4): Shows the values of (t), (R_S), (R_0) and (S) at various heating voltage (V_H) values for the TGS2612 sensor.

V_H(v)	R_0 (K Ω)	R_S (K Ω)	S	t (Sec)
3	69.471	7.794	0.88781	87
3.5	80.379	7.501	0.90668	82
4	94.158	7.221	0.92331	79
4.5	124.81	6.897	0.94474	76
5	165.200	6.423	0.96112	73
5.5	298.137	5.921	0.98014	72
6	220.006	6.334	0.97121	78
6.5	134.515	6.711	0.95011	81
7	120.406	6.821	0.94335	94

Similarly, for the last three voltages of this sensor, the stabilization time increased and the sensitivity decreased as the heating voltage increased, due to the same reason as before. However, we noticed an increase in resistance after the value of 5.5V instead of a decrease. This confirms our observation that the properties of the sensor change when the heating voltage exceeds the recommended values.

We also calculated the average of these times at all heating voltages and found that this sensor can detect gas within a time of (t=80.2 Sec).

The following Figure (6) shows the changes of R_S, S, t depending on the heating voltage:

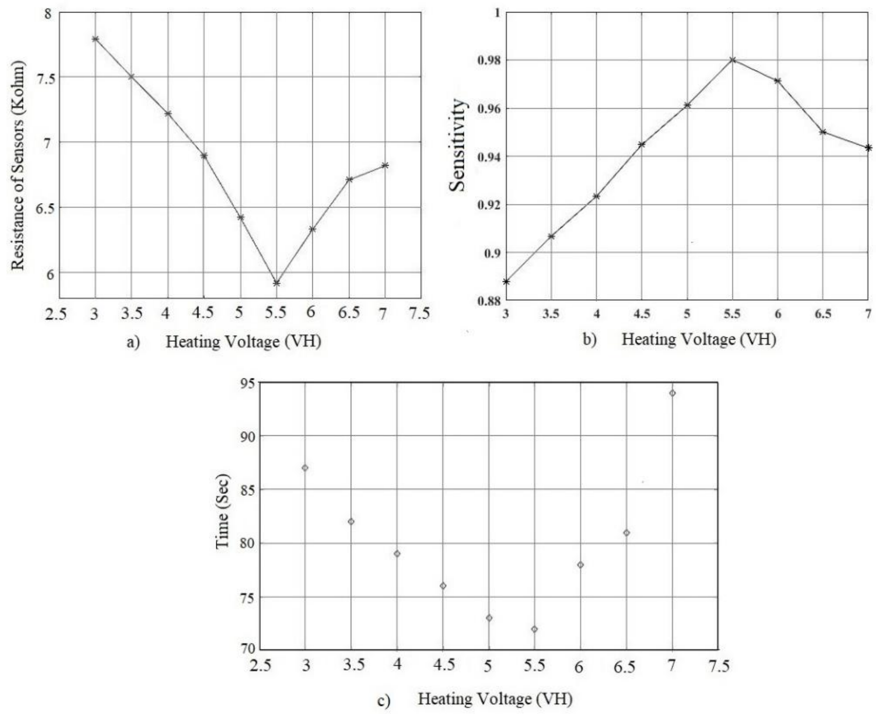

Figure (6): a): Shows the changes in resistance (R_S) with heating voltage (V_H) for the TGS2612 sensor. b): Shows Changes in sensitivity (S) with heating voltage for the TGS2612 sensor. c): Shows Changes in stabilization time with heating voltage for the TGS2612 sensor.

3.5 For TGS2620:

Table (5) shows the time taken by this sensor to reach stability, stable resistance (R_S), initial resistance (R_0) and sensitivity (S) at various heating voltage values.

Table (5): Shows the values of (t), (R_S), (R_0) and (S) at various heating voltage (V_H) values for the TGS2620 sensor.

V_H(v)	R_0 (K Ω)	R_S (K Ω)	S	t (Sec)
3	32.993	3.913	0.8814	93
3.5	34.617	3.451	0.90031	88
4	38.418	3.027	0.92121	85
4.5	46.572	2.541	0.94544	81
5	53.951	2.157	0.96002	78
5.5	78.641	1.852	0.97645	75
6	36.270	2.334	0.93565	83
6.5	30.612	2.712	0.91141	87
7	23.650	2.572	0.89125	99

Similarly, for the last three voltages of this sensor, the stabilization time increased and the sensitivity decreased as the heating voltage increased. Additionally, here the sensor's resistance increased, which contradicts the principle of semiconductors and indicates that the sensor is damaged. We also calculated the average of these times at all heating voltages and found that this sensor can detect gas within a time of (85.4 Sec).

The following Figure (7) shows the changes of R_S, S, t depending on the heating voltage :

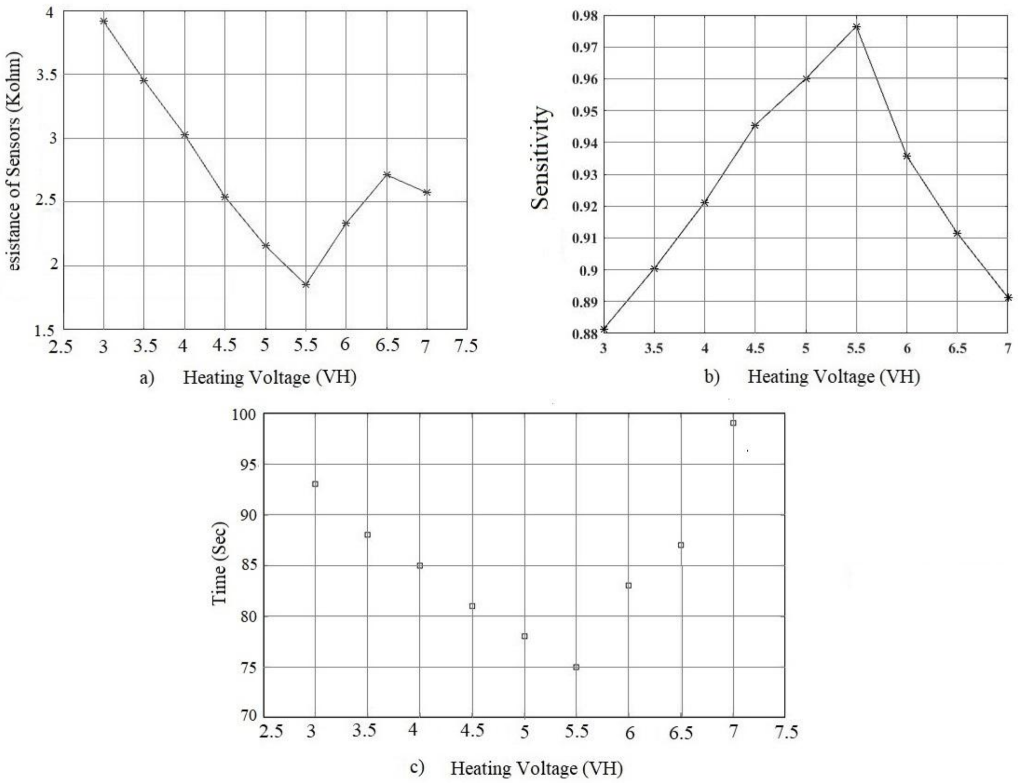

Figure (7): a): Shows the changes in resistance (R_S) with heating voltage (V_H) for the TGS2620 sensor. b): Shows Changes in sensitivity (S) with heating voltage for the TGS2620 sensor. c): Shows Changes in stabilization time with heating voltage for the TGS2620 sensor.

3.6 For TGS2630:

Similarly, Table (6) shows the time taken by this sensor to reach stability, stable resistance (R_S), initial resistance (R_0) and sensitivity (S) at various heating voltage values.

Table (6): Shows the values of (t), (R_S), (R_0) and (S) at various heating voltage (V_H) values for the TGS2630 sensor.

V_H(v)	R_0 (K Ω)	R_S (K Ω)	S	t (Sec)
3	41.317	6.013	0.85447	122
3.5	46.449	5.874	0.87354	117
4	54.186	5.624	0.89621	114
4.5	58.237	5.221	0.91035	111
5	74.741	4.989	0.93325	108
5.5	92.491	4.521	0.95112	104
6	76.713	4.253	0.94456	107
6.5	50.248	3.947	0.92145	112
7	36.119	3.539	0.90202	127

Similarly, for the last three voltages of this sensor, the stabilization time increased and the sensitivity decreased as the heating voltage increased, due to the same reason as before. We also calculated the average of these times at all heating voltages and found that this sensor can detect gas within a time of (t=113.5 Sec).

The following Figure (8) shows the changes of R_S, S, t depending on the heating voltage:

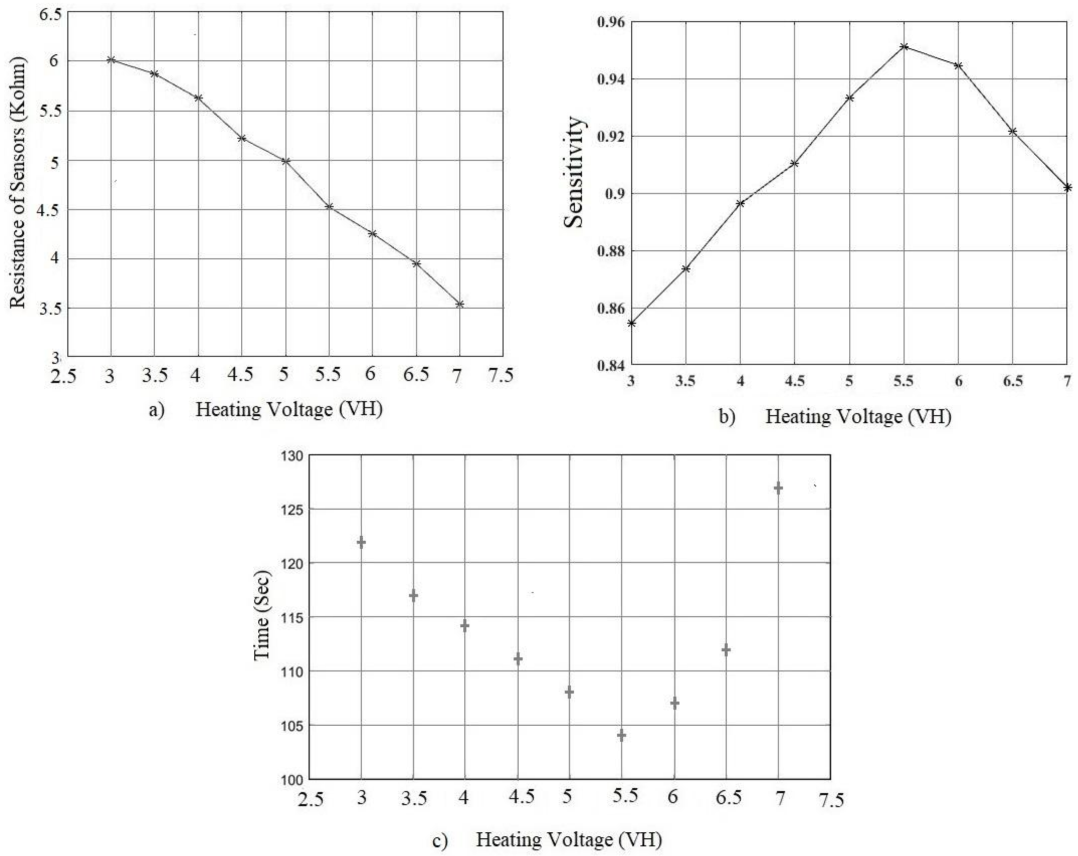

Figure (8): a): Shows the changes in resistance (R_S) with heating voltage (V_H) for the TGS2630 sensor. b): Shows Changes in sensitivity (S) with heating voltage for the TGS2630 sensor. c): Shows Changes in stabilization time with heating voltage for the TGS2630 sensor.

We have compiled the stability times for all sensors within the figure (9):

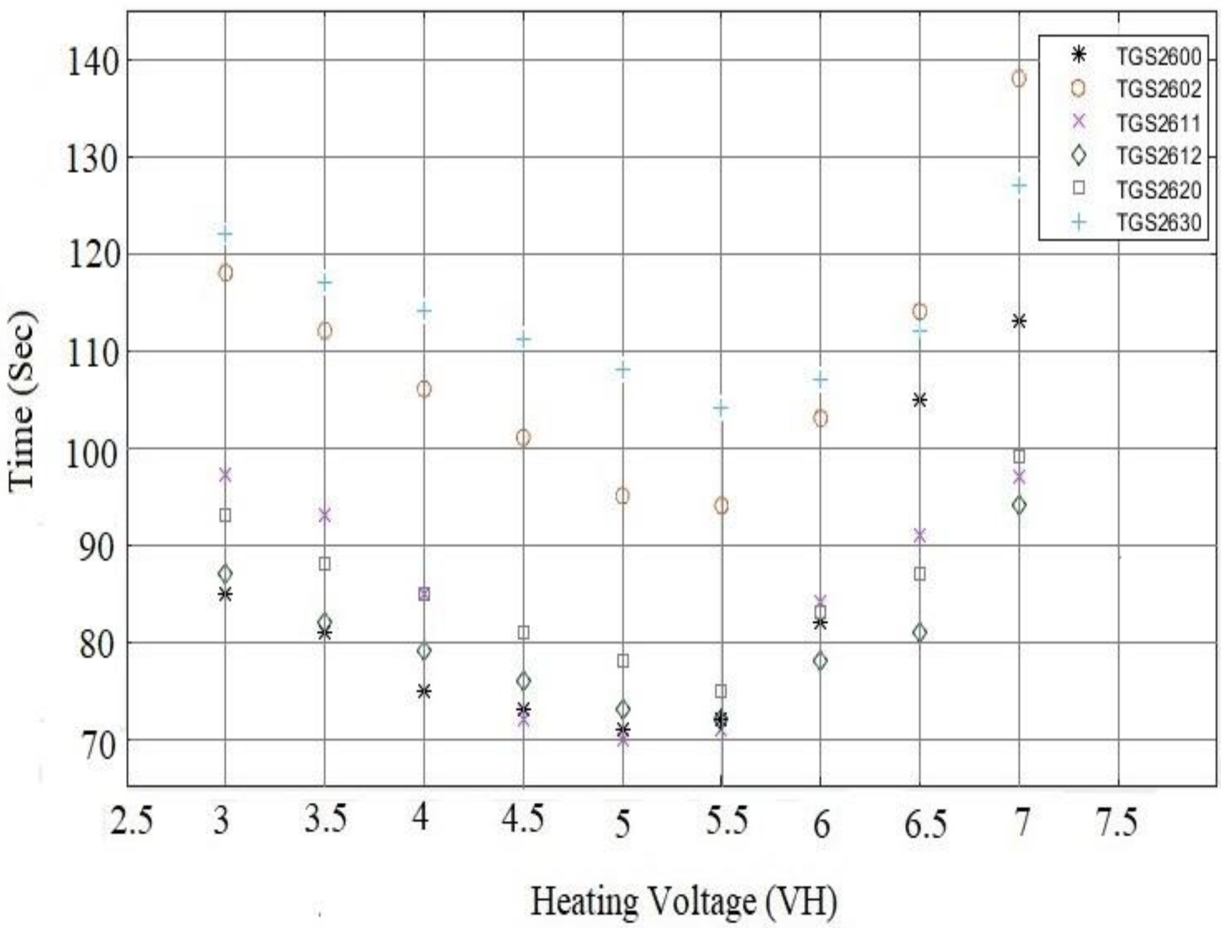

Figure (9): Shows Stability times at various heating voltages for all sensors

Based on the findings, the behavior of the sensors can be categorized into distinct case:

- For the sensors (TGS2600, TGS2602, TGS2611), the increase in heating voltage to 7V led to a continued decrease in stable resistance value, but the stabilization time started to increase after 5V, which is not desirable when selecting the sensor for any circuit.
- For the sensors (TGS2612, TGS2620, TGS2630), the increase in heating voltage to 5.5V led to a continued decrease in the stable resistance value as well as a decrease in stabilization time. However, when the voltage was increased to 7V, the sensor's resistance started to increase while the stabilization time continued to increase.
- For all sensors, increasing the heating voltage led to an increase in sensitivity up to 5.5V, after that, further increases in heating voltage resulted in a decrease in sensitivity.
- When the sensors were reused, we found that they were no longer suitable for operation, as the resulting values became unstable and did not match what we had previously obtained.

Therefore, we can recommend that the best operating points for these sensors when exposed to this gas are shown in the following Table (7):

Table (7): Operating Points of the Sensor Set

Sensors	V_H (V)	(K Ω) R_S	S	t(Sec)
TGS2600	5.5	22.768	0.96121	72
2602TGS	5.5	26.454	0.93454	94
TGS2611	5.5	2.978	0.97414	71
TGS2612	5.5	5.921	0.98014	72
TGS2620	5.5	1.852	0.97645	75
TGS2630	5.5	4.521	0.95112	104

One of the main objectives of studying any sensor or set of sensors is the time it takes for the sensor to detect any gas and stabilize. Therefore, we can determine the response times for this set as a whole by taking the average of these times of the sensor set at the previous heating voltages, as shown in the following Table (8):

Table (8): Stabilization times of the sensor set at various heating voltage (V_H) values.

V_H(v)	3	3.5	4	4.5	5	5.5	6	6.5	7
t (Sec) set of Sensors	100.33	95.5	90.66	85.66	82.5	81.33	89.5	98.33	111.33

We observe from the previous table that the best times were for the voltages (4.5-5-5.5) V, with the best being (5.5V) due to the lower resistance value compared to the voltages (4.5-5) V. The following Figure (10) shows the times for the sensor set.

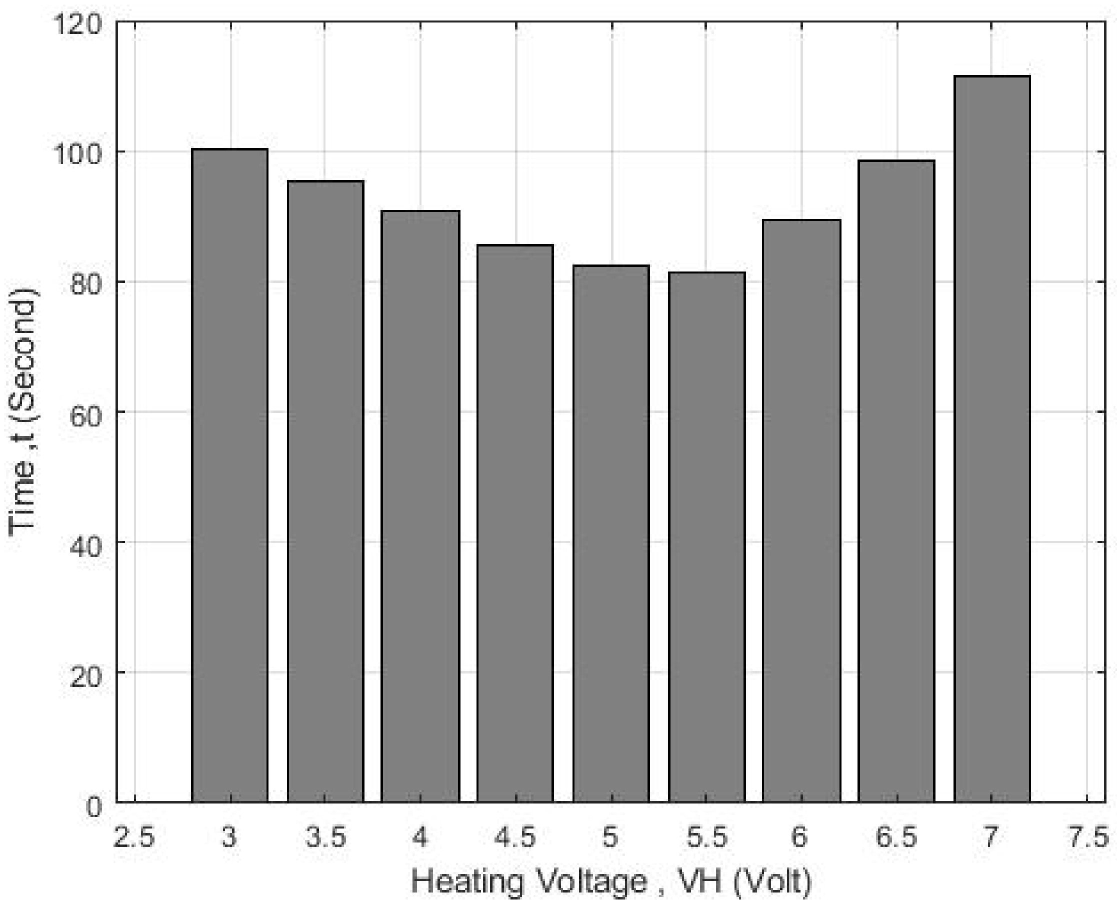

Figure (10): Stabilization times of the sensor set at various heating voltage (V_H) values.

4. Conclusion:

- In this research, we studied the behavior of a set of gas sensors towards domestic gas by varying the heating voltage (V_H) of the sensor layer.
- We determined the operating points for each sensor individually, which are represented by the heating voltage (V_H), stable resistance (R_S), and stabilization time (t).
- We concluded that the best heating voltage for the sensor set as a whole is VH=5.5V, as this voltage recorded the best time and the lowest stable resistance.
- We recommend not applying voltages higher than V_H=5.5V to avoid damaging the sensor layer.

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