



Temperature Control Circuit for Gas Sensor

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Abstract: This paper presents a Temperature Control Circuit for a microhotplate based gas sensor fabricated in standard 0.35/0.18 μ m CMOS technology. The on-chip microhotplate provide very high temperatures (between 200°C and 400°C), which are necessary for the normal operation of metal oxide sensing layers. The complete temperature control circuit comprises of 10-bit A/D converter, low pass filter, two 10-bit D/A converters, two operational amplifiers and a digital controller (Vertex-IV FPGA). The required temperature is achieved by sourcing suitable amount of current to the gas sensor through a current steering 10-bit DAC.

Keywords: testing of gas sensor; temperature control circuit; noise analysis of amplifier.

I. Introduction

Highly sensitive gas detectors have become important in air quality control, home automation, in military for security purposes and many other industries that use gases as a raw material. Thus detection and quantification of gaseous species in air as contaminants at low cost is becoming important. It has been the aspiration of researchers for more than 20 years to combine the different parts of a gas sensor with microelectronics in order to create an integrated or smart gas sensor. However, the single most significant impediment to having the widespread application of gas sensors is their price. Most of the gas sensors marketed today cost well in excess of \$10 and are embedded in instruments that then brings the price up to and excess of \$500.[1]

The different types of gas sensors available in the market are electrochemical sensors, catalytic field effect sensor, solid state sensors, and catalytic sensors [2-Sensors for Toxic Gas detection]. It has been found out that solid-state gas-sensors are the best candidates for the development of commercial gas-sensors for a wide range of applications. Solid-state chemical sensors in general have been widely used, but they still suffer from limited measurement accuracy and problems of long-time stability. However, recent advances in nanotechnology are providing the opportunity to dramatically increase the performance of real solid-state gas-sensors. A characteristic of solid state gas-sensors is the reversible interaction of the gas with the surface of a solid-state material.

Organic (as conducting polymers [2], porphyrins and phthalocyanines [3]) or inorganic (as semiconducting metal oxides [4, 5]) materials, deposited in the form of thick or thin films, are used as active layers in solid state gas sensing devices. [3- lombardi]. Semiconducting metal oxides are among the most promising solid state gas sensors owing to their high sensitivity to a broad range of chemicals, reduced size and weight, low power consumption, compatibility with silicon technology, possibility to produce these devices by means of cheap techniques compatible with industrial scaling up such as sputtering or evaporation and condensation methods(sensor 12-17023). Metal oxides (e.g. tin oxide [2], zinc oxide [3]) react with different gases at fairly high temperatures (200°C-400°C) and their resistance changes function of the gas concentration. Therefore, from the change in resistance and the optimum temperature of operation one can deduce the concentration and the type of gas. Hence, the temperature of a sensing film can affect a variety of factors, including the film's base conductance, the quantity of gases it will absorb, and the rates of reactions between adsorbents on its surface. [4-5 microhotplate and session 2259].

A simple semiconducting metal oxide gas sensor basically composed of a substrate in alumina or silicon (on which the sensing layer is deposited), the electrodes (to measure the resistance changes of the sensing film) and the Joule-effect based heater to reach the optimum sensing temperature.. The heating resistance is in platinum and its temperature coefficient is linear over the gas-sensor operative temperature range. The temperature is measured using a platinum resistance thermometer (PRT) as a temperature sensor. The Gas sensor chip used has six pads two each for the heater, PRT and the sensing material. The resistances of heater and PRT are 746 Ω and 3.946K Ω respectively as shown in Figure 1 and 2.

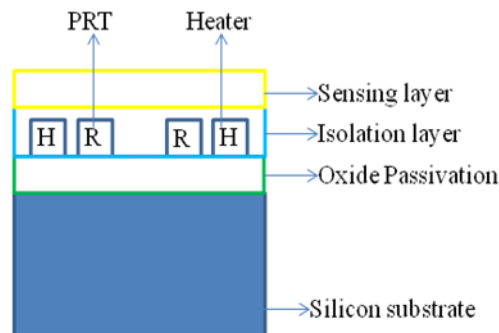


Figure 1 Cross sectional view of Gas Sensor



Figure 2 Gas Sensor Chip

The fundamental blocks necessary for the realization of a high-selectivity gas detection system is based on the use of semiconductor chemical sensors and the high selectivity has to be obtained by using a stable temperature control circuit. The system consists of a semiconductor sensing device, an A/D integrated circuit consisting of a dedicated conditioning topology for the read-out of the data coming from the sensor and a system for digital processing of the acquired data.

Control circuits of heaters for flow and gas sensors have been reported in several ways in the literature [2-8, 9(mixed mode temperature control)]. Most of the employed methods are usually based on a constant power heating rather than on the direct control of the temperature. Nevertheless, because of the dependence of the heater temperature on external factors such as humidity ambient temperature, airflow, methods based on constant heating power have, in general, to be avoided [9]. The temperature is thus controlled by directly measuring the heater resistance. In reference [2] a Pulse Width Modulation (PWM) approach is used to directly control the heater resistance (and hence temperature). Nevertheless such approach has the disadvantage of high injected noise and high ripple for accurate control (accuracy lower than 1°C). A simple (our controller) avoids all these problems. In this topology, the voltage drop across the temperature sensor is amplified and low-pass filtered (LPF). The analog output of the LPF is converted to the digital domain using 10-bit successive approximation ADC. The inputs to the digital controller unit are the feedback signal from the microhotplate temperature and the 10 bit reference temperature. The output of the controller is converted to the analog domain using a 10 bit current steering DAC.

II. Testing of Gas Sensor

The gas sensor was tested to observe its behavior with current. On passing a current pulse to the heater from a current source, it was observed that the heater's resistance viz. PRT resistance increased with an increase in current (i.e. temperature). It can be seen from the plot (Figure 3) that the PRT resistance increases with increase in heater's current but not in a purely linear fashion. Three combinations were simulated for different current conditions. Previous combination is a plot to test the response of the gas sensor for various current values. 1st combination gives the output response of gas sensor with current having unequal pulse width. 2nd combination displays the output response of gas sensor with current having equal pulse width. All the three combinations conclude that gas sensor's behavior becomes non-linear with higher values of current. Figure 4 also shows that the output voltage at the PRT node increases nonlinearly for higher values of heater's current.

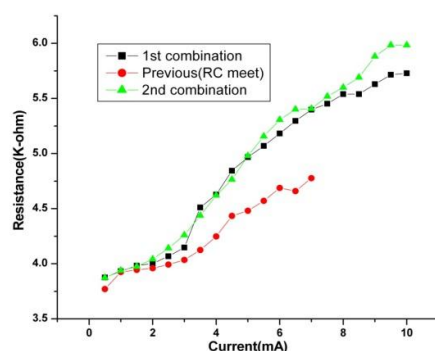


Figure 3 Current vs. Resistance Plot

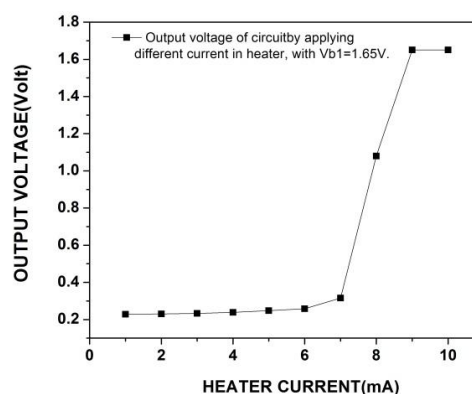
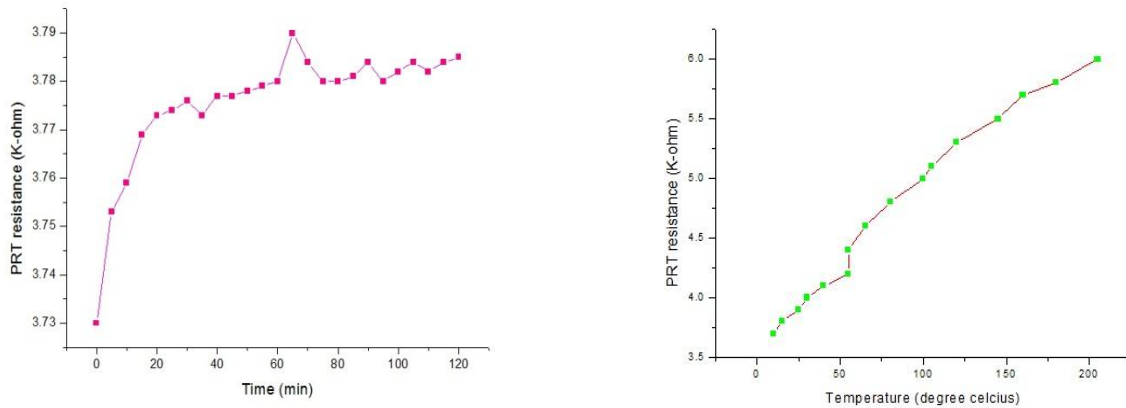


Figure 4 Heater Current vs. Output Voltage plot

The behavior of gas sensor is also observed with time for a constant value of current. A current of 1mA is pumped to the heater of gas sensor for a long time period (2 hours). The PRT resistance is varied with time as shown in Figure 5.



This graph shows that the PRT resistance is varied from 3.73K Ω to 3.79K Ω . For this variation in resistance value Temperature is also changed. The change in temperature is observed by the next plot. This plot shows that with PRT resistance, temperature changes as shown in Figure 6. From this plot it concludes that for the change in value of PRT resistance from 3.73K Ω to 3.79K Ω the corresponding temperature variation is 10-20 $^{\circ}$ C. It results in cross sensitivity of gases.

The gases are detected with temperature that is achieved by applying current to Heater of Gas Sensor. A plot is obtained between Heater current and detected gases for different temperatures as shown in Figure 7.

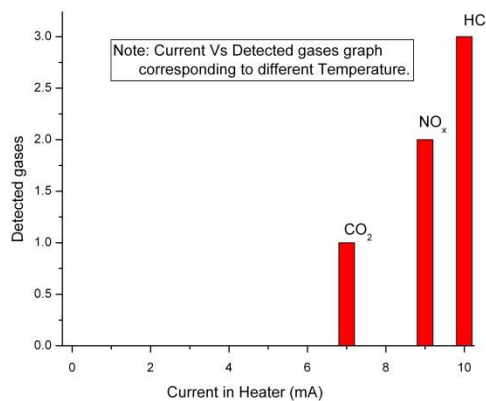


Figure 7 Heater Current vs. Detected Gases Plot

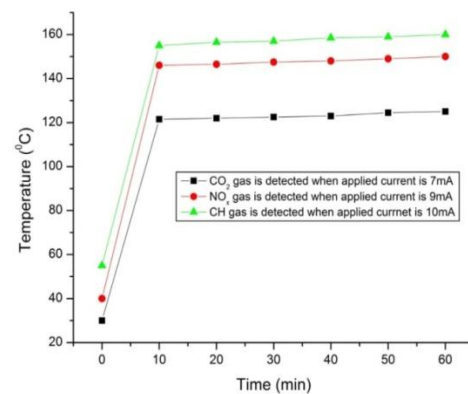
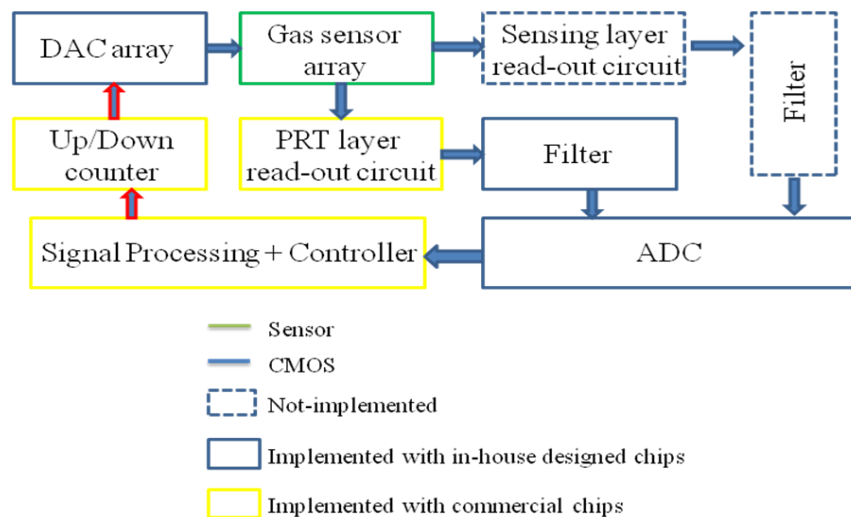


Figure 8 Time vs. Temperature Plot

In order to see the temperature of detected gas, constant currents of 7mA, 9mA, 10mA are applied for time period of 1hour as shown in Figure 8. It shows that CO₂ gas is detected at 120 $^{\circ}$ C, NO_x is detected at 142 $^{\circ}$ C and CH gas (organic gas) is detected at 155 $^{\circ}$ C temperature. From last two gases temperature difference is 13 $^{\circ}$ C. So, there is chance of cross sensitivity of gases as said from Figure 6. To resolve this problem and to maintain constant temperature, a temperature control circuit is designed. It is discussed next.

III. Temperature Control Circuit

The objective of this circuit is to stabilize the current flowing through the gas sensor in order to maintain a constant temperature for a particular gas. A temperature control circuit consists of a current steering DAC, a gas sensor, a technology independent operational amplifier, a differential amplifier; a low pass filter (LPF), a SAR ADC and a digital control circuit is in Figure 9. A current steering DAC was chosen for providing a current input to the heater since the performance of current steering DAC was better over voltage DAC in terms of noise. Since the heater and PRT are thermally connected (though electrically isolated), an increase in the heater current causes an increase in the PRT resistance in non linear fashion at higher values of heater's current. The output voltage at the PRT node also increases nonlinearly for higher values of heater's current.



Note – Currently all the experiments are done with one gas sensor and one DAC.

Figure 9 Temperature Control Circuit

Since the output of the gas sensor is a resistance (sensor layers are floating resistances) and the ADC input is either voltage or current so, a signal conditioning circuit has to be employed to convert the resistance into voltage and to match the output with the input working range of the ADC. Two feedback operational amplifiers have been used in this circuit for better noise performance. The detailed noise analysis of amplifier is discussed next.

IV. Noise analysis of Amplifier

The conditioning circuit of temperature control circuit for gas sensor consists of two amplifiers, a low pass filter and a buffer is shown in Figure 10. It can be easily seen that the gas sensor (PRT layer) is connected in feedback of the amplifier. It is placed in feedback for getting better noise performance. The output noise response was observed with the 2nd amplifier gain kept constant at 100V/V and the gas sensor in feedback to the 1st amplifier (variable gain).

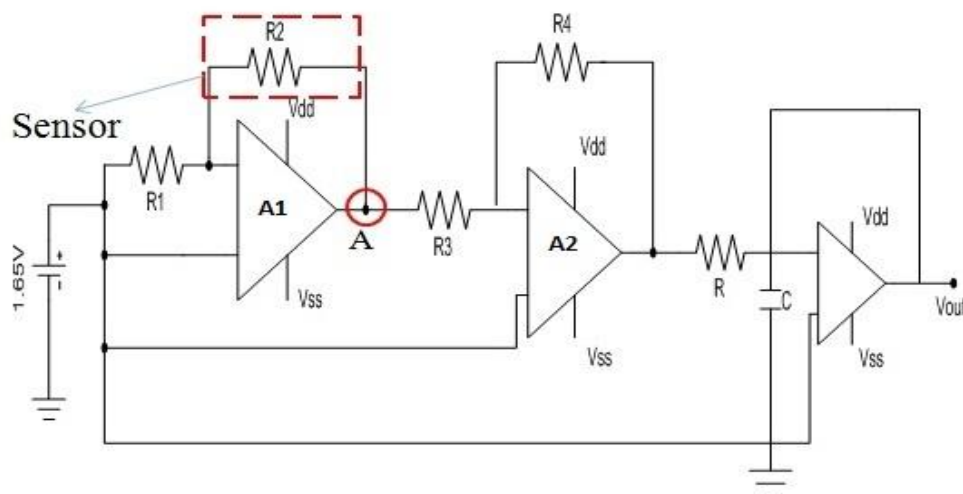


Figure 10 Conditioning Circuit for Gas Sensor

It can be seen from Figure 11 that noise performance of this configuration is better at gain of 1st amplifier is A1=5. And the PRT resistance of gas sensor is measured at point 'A' as shown in Figure 12.

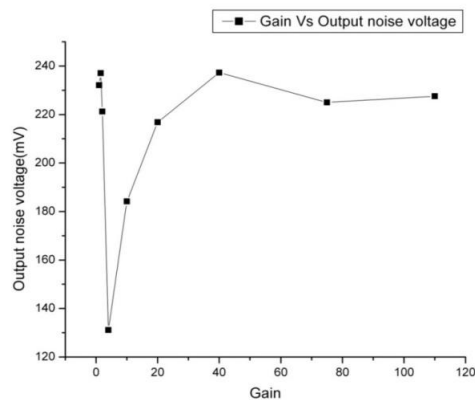


Figure 11 Gain vs. output noise plot

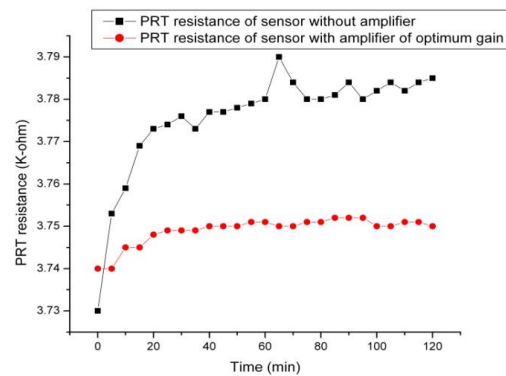


Figure 12 PRT resistances vs. time plot for constant current of 1mA

From Figure 12, it can be easily seen that the variations in PRT resistance are approximately negligible. It means that the variation in temperature is also negligible. The problem of cross sensitivity is removed by this circuit. The noise of the first amplifier is measured practically. In order to see this, the practical noise is correct or not theoretically it is also calculated by a very popular feedback method i.e. asymptotic gain method. It is chosen for its exactness. The equivalent circuit of first feedback amplifier is shown in Figure 13.

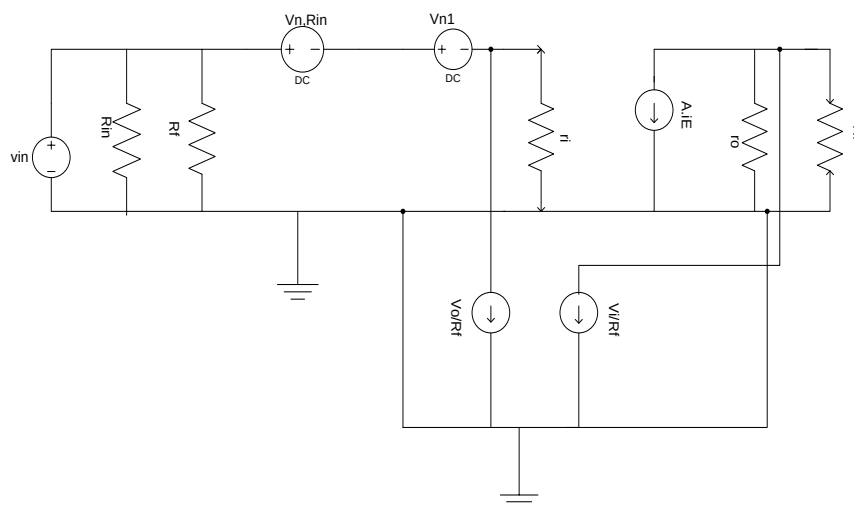


Figure 13 Equivalent circuit of feedback amplifier

Equivalent circuit for the noise analysis of the feedback amplifier is shown in the figure. The asymptotic gain is defined as:

$$G = ((G_0 + KT)/(1 + T)) = -(r_o R_f / (1 + r_o / R_f))$$

Where, G is the closed loop gain, A is the open loop gain K is asymptotic term,

$$K = -(r_o / R_{in} - A \cdot r_o / (r_o \parallel R_f)) \dots \dots \dots (i)$$

G_0 is direct transmission gain

$$G_0 = (r_o / R_{in}) \dots \dots \dots (ii)$$

and T is loop gain or return ratio. This return ratio is calculated by

$$T = (r_o / (r_o + R_f)) * (A \cdot r_o / R_f) * (1 / r_i \parallel (R_f + R_{in})) \dots \dots \dots (iii)$$

By substituting the resistance values of the amplifier, the output referred noise is 130mV. It is same as that of practical noise. It is also verified by taking certain values. It is shown in Table 1.

V. Results

In this section we are going to discuss about the noise analysis results. We use an oscilloscope to determine the value of output referred noise. There are various noises are obtained for combination of amplifiers, noise of filter, noise of temperature control circuit.

In this section various results are shown in which the mean value of the noise is considered from the Figures.

1. Noise of amplifier when PRT is at input
2. Noise of amplifier when PRT is in feedback

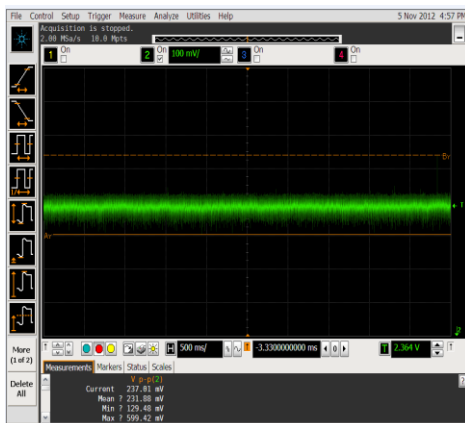


Figure 14 Output noise of Amp. when PRT at input

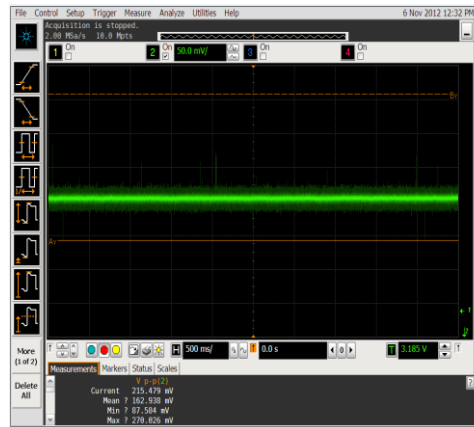


Figure15 Output noise of Amp. When PRT in feedback

The value of output noise of the amplifier is 231.88mV in first case while in second case the value of output noise is 162.398mV. By this it can be easily seen that noise performance is better in second case.

2. Output noise of LPF with $f_c=1\text{MHz}$

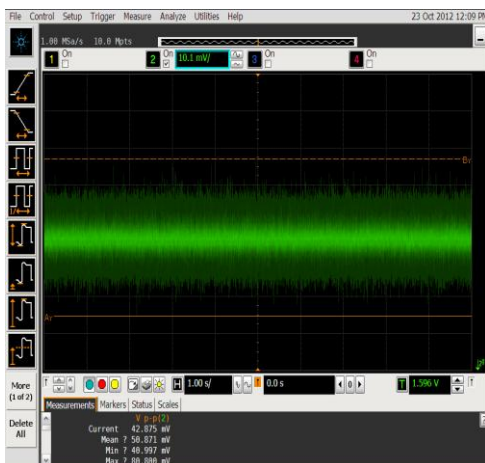


Figure 15 Output noise of filter

3. Output noise of Temperature Control Circuit

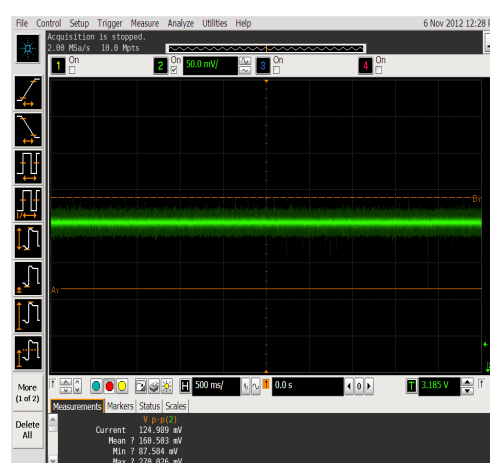


Figure 16 Output noise of Temperature Control Circuit

The value of output noise of filter is 50.871mV. The output noise of temperature control circuit is 160.503mV. These are the practical values of the noises. It is verified with the theoretical results as given in Table 1.

Table 1

Ro(Ω)	Practical noise(mV)	Theoretical noise(mV)
100	131.5	130.23
150	182.5	185.9
200	216.0	229.36
300	225.5	224.31

From this table, it concludes that the practical and theoretical noises are approximately same.

VII. Conclusion

In this paper we test the gas sensor and Find out its behaviour. Gas sensor's resistance is continuously varied for a constant value of applied current. It results in a cross sensitivity problem. To remove it, we proposed a temperature control circuit and to find out its performance we do noise analysis. After evaluating the practical and theoretical noises results we came to a conclusion that proposed scheme is better for gas sensor temperature stability.

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