Design considerations for monolithic integration of a micro hotplate temperature controller in a MEMS gas sensor.

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Abstract — **A control system to regulate the temperature of the micro hotplate in a MEMS gas sensor is presented. The controlelement, called micro hotplate, is comprised of a micro heater and a temperature sensor, both made with polysilicon, located near each other. This material has a Temperature Coefficient of Resistance (TCR) that is the basis for the design of the temperature controller of the gas sensor system. A high temperature between 250 and 400 °C is needed to produce a chemical reaction between the gas and the sensing film, hence a reliable temperature control for the micro hotplate is desired. Thermal insulation of the circuitry from the heating element, having a monolithic sensor system, and low power consumption, are the main specifications for the system. This is obtained by means of a micro pit realized with MEMS micromachining processes. The analysis of the circuit proposed to fulfill these characteristics is presented, for its future integration with a standard CMOS technology. A trade off is established between the sensor structure parameters and the circuit design.**

Keywords — **Control, FGMOS, MEMS, Gas sensor**

I. INTRODUCTION

A Floating Gate MOSFET (FGMOSFET) sensor that takes advantage of the sensitivity of the threshold voltage of a to charge derived from the chemical reaction between the sensing layer (metallic oxide) and either a reducing or oxidizing gas, is proposed.. It is a principle that has been used previously in pH sensors in liquid solutions, but fabricated with nonstandard technologies [1, 2]. The gas sensor, along with its suggested control and signal processing circuits, can be designed and fabricated with commercial CMOS standard technology compatible with MEMS processes.

The chemical reaction between the gas and the sensing film is usually carried out at temperatures between 250 and 400 °C. In order to locally heat the sensing area in the integrated circuit, structures as micro hotplates [3, 4, 5, 6], can be designed and integrated by the standard technology with a polysilicon micro heater . Then, if the objective is to have the sensor and the electronics on the same silicon substrate heating insulation between the micro hotplate and the associated circuitry is required. This is obtained by means of a micro pit realized with MEMS micromachining processes using anisotropic etching solutions such as Tetramethylammonium hydroxide (TMAH) or Ethylenediamine pyrocatechol (EDP).Also, factors such as silicon area and power consumption are critical in the design of each one of the parts that conform the whole circuit.

In the case of the micro hotplate temperature control system, a simple configuration like an analog proportional control is proposed, implemented with an operational amplifier. The main objectives in the design of this system are the monolithic integration of a circuit with low power consumption, use of a small silicon area, simplicity and stability of the integrated sensor [7].

II. DESIGN CONSIDERATIONS

The heating element, called micro hotplate, is comprised of a micro heater and a temperature sensor, both made with polysilicon, located near each other, within a thin membrane obtained with micromachining etching processes as done for MEMS structures. Polysilicon varies its resistance with temperature variations (TCR) and this characteristic is used in the design of the temperature controller. Joule effect is the cause of polysilicon heating, whose temperature depends on the magnitude of the voltage applied across the micro heater terminals. The design of the integrated resistance is important if low power is a target. Therefore, the sheet resistance of the polysilicon layer used in a given CMOS technology should be taken in account. Also, a low resistance value at room temperature is highly convenient, since low voltage values can be used to raise the micro heater temperature to the desired operating range. This establishes a guideline for the geometric design of the micro heater, together with the specification of a uniform temperature distribution of the heated zone over the thin membrane. The same guidelines apply for the polysilicon used as the temperature sensor. A change in resistance through the operating temperature range used for the micro hotplate, results in a voltage drop change across the temperature sensor, when biased with a constant current source. The layout of the microheater and the temperature sensor is shown in Fig. 1, where the sensor and the heater are in close proximity.

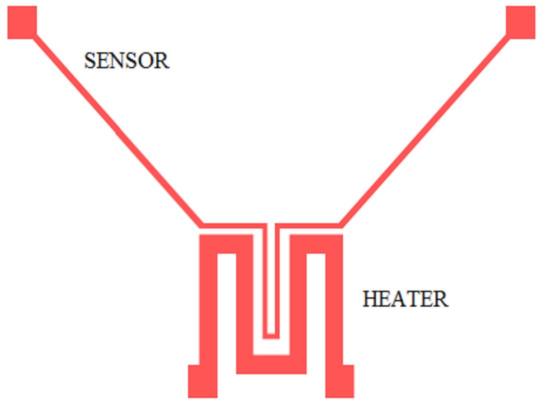

Fig. 1. Polysilicon heater and sensor.

III. TCR CHARACTERIZATION

The design reported here will be fabricated with AMI technology (n-well, double poly, double metal), by MOSIS. Both, the microheater and the sensor will be made with Poly1. Test structures were designed and fabricated previously with four different geometries, for TCR characterization purposes. By knowing TCR is useful to correlate temperature variations with applied power. When voltage is applied to the micro heater, heat is transmitted by conduction to the sensor then increasing its temperature, with the corresponding resistance change. Hence a plot can be made to obtain the microheater efficiency in °C/mW, as power applied is known and resistance can me measured. For the correct design of the control circuitry of the sensor system, it is also important to know the resistance dependence with temperature,. This gives the opportunity to simulate different circuit configurations prior to the fabrication of a prototype chip, until an optimum design is available. Then, in order to calibrate and set-up correctly the controller, the TCR must be measured. The polysilicon sensor works as a thermistor, which is a resistor whose resistance varies with temperature. The TCR can be negative, meaning that the resistance of the thermistor will decrease if temperature increases, or positive, as the thermistor behaves in the opposite way, an increase in temperature causes an increase in resistance.

To obtain the TCR value of Poly1, a DIP packaged chip was heated up to a known temperature with an external heat source. Heating was made in 20 °C steps, from room temperature, up to 200 °C. A constant voltage was applied and the current through the resistor was measured. The relation of the temperature of the micro heater with resistance is given by:

$$\Delta T = T - T_0 = \alpha \frac{\Delta R}{R_0} \tag{1}$$

where T_0 refers to room temperature, R_0 is the base resistance at T_0 and α stands for 1/TCR. R_0 for the microheater is 5.58 kΩ and for the sensor is 1.17 kΩ. Fig. 2 shows the result of the characterization of a sensor and a heater resistor, corresponding to a TCR value of 8.84E-4/ºC along with the results of a COMSOL (incluir significado) simulation of a low resistance heater, giving a value of 8.04E-4/°C. A linear fitting was made from the experimental results to obtain an expression describing the temperature dependence of resistance, as expressed in (1). It should be noted that although two lines with different slopes are plotted for the experimental characterization, the TCR value for both elements is the same, which means that it is independent from the geometry used. A close agreement between experimental and the theoretical analysis with COMSOL data is noted.

IV. CONTROL SYSTEM DESIGN AND SIMULATIONS

The control system for the microhotplate is shown in Fig 3. An operational amplifier drives a MOS transistor, switching the current for the heating element that is connected to a pulsed voltage source. The sensor resistor is biased with a constant current source. As the sensor resistance changes, the voltage drop across it will be the feedback signal in the inverting input of the op amp. Connected to the non-inverting input there is a reference voltage corresponding to the set-point of the temperature controller. This voltage is the one required by the micro heater element to reach a given operating temperature needed to favor the reaction between the sensitive film and the gas. The voltage at the sensor can be obtained easily with the constant current source value and the resistance value. Using (1), the sensor resistance value corresponding to the operating temperature can be calculated and then the set-point voltage to be applied can be obtained. This completes the control loop of the system proposed.

The system was simulated using a voltage bias of 1.5V, a two stage compensated op amp with an area of 84 µm x 147.2 µm, a MOS transistor with W/L=120µm/1.6µm and a pulsed current source of 100 µA. The set point was fixed to 200mV, corresponding to a temperature of T= 296 °C.

PSPICE simulations were done to verify the performance of the system. A MOS transistor is used as a power transistor for the heater. This MOSFET was designed taking into account the current needed for the heater at the operating temperature and the corresponding resistance. Fig. 4 shows how the voltage at the sensor changes over time as its resistance increases due to temperature increase and the gate voltage of the MOSFET switches correspondingly.

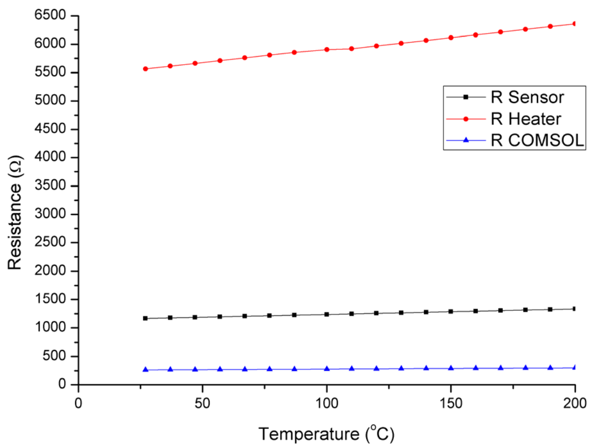

Fig. 2. Resistance vs.Temperature for Poly1 TCR characterization.

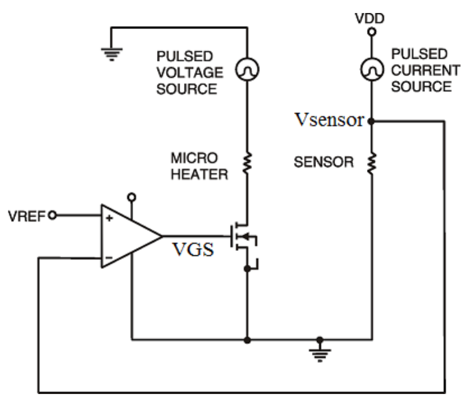

Fig. 3. Temperature control system.

Using an equivalent circuit, in wich the microheater and sensor resistors are replaced by suitable components, the overall behavior of the control system was evaluated. This circuit is shown in Fig. 5.

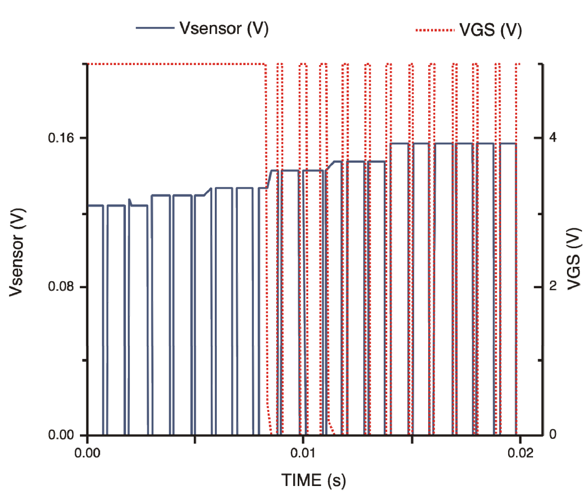

Fig. 4. Sensor voltage vs. Time.

In order to observe the transient response of the system, the micro heater can be substituted by an RC circuit to include the time constant for the heating and cooling of this resistor. With a pulsed current source, the voltage at the capacitor can be used as the temperature at the micro heater. The electro-thermal coupling between the heater and the sensor is substituted with a voltage-dependant voltage source.

As can be seen from Fig. 3, the change of temperature, and in the equivalent circuit, the change of voltage at the capacitor, causes a voltage change at the sensor, suitable to be used as a feedback. The sensor resistor as such is not needed in the equivalent circuit because the voltage dependant source provides this feedback voltage, including any offset caused by thermal conduction. The single power MOSFET is now an n-channel/p-channel pair, allowing the capacitor to charge and discharge when the op-amp output changes from high to low and vice versa. This circuit is shown in Fig. 5.

An op-amp fulfilling the requirements stated above, of small area and low power consumption, was chosen, including also a small input offset. This feature is needed because the voltage variation at the sensor is small. A way to overcome this problem is to bias the sensor resistor with a larger current, but this approach compromises the low power condition of the system. The schematic of the two-stage compensated op-amp is shown in Fig. 6.

A suitable resistor model to include the TCR value was used, and a temperature sweep was performed from 27ºC to 450ºC, fixing the other devices in the circuit to maintain 27ºC. This simulation was expected to give the behavior of the control circuit when the voltage at the sensor approaches the set-point voltage.

V. Results

COMSOL simulations gave a time constant of 12ms, as shown in Fig. 7, for different voltage values applied to the micro heater.

The final layout of the MOSFET is shown in Fig. 8, designed with an interdigitated configuration to optimize the area used by this power transistor and to support the current demanded by the system to achieve the temperature range specified.

From the equivalent circuit mentioned before, the simulation shows that the control system works as expected, keeping the power MOSFET on until the voltage at the sensor reaches the reference voltage and shutting it off. Then, according to the cooling of the heater, the transistor will be on and off maintaining the microhotplate at the operating temperature. This is shown in Fig. 9 and Fig. 10 shows the layout of the op-amp.

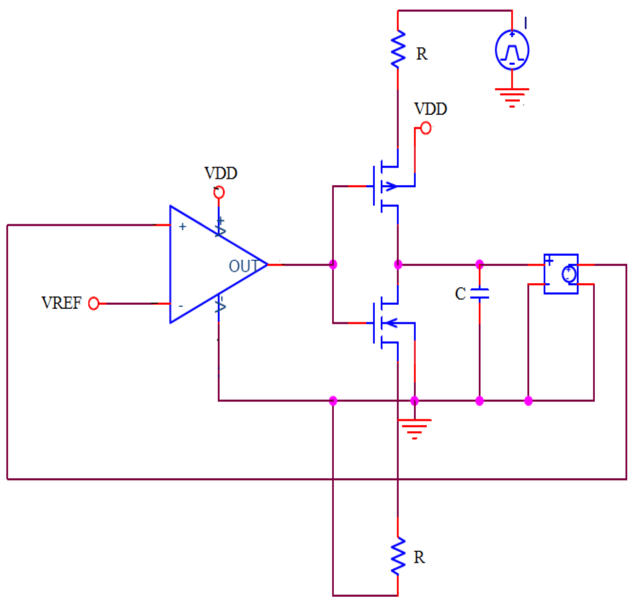

Fig. 5. Temperature control equivalent circuit.

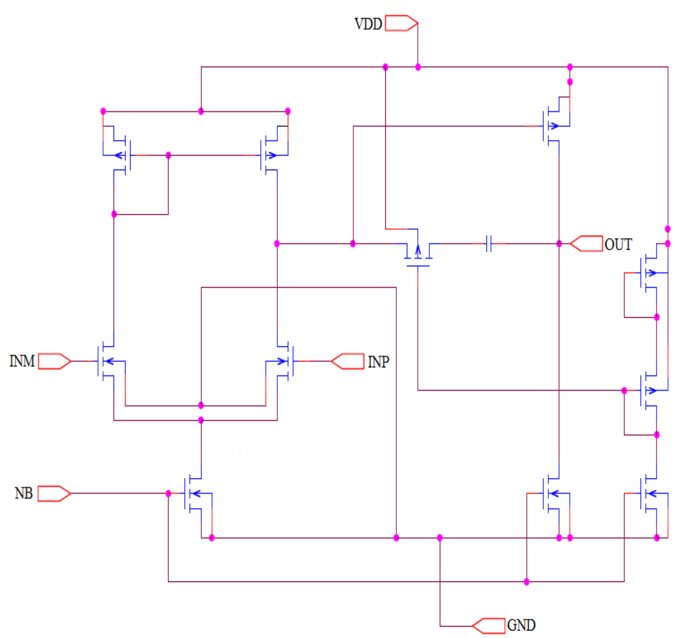

Fig. 6. Schematic of the Op-amp used in the temperature controller circuit.

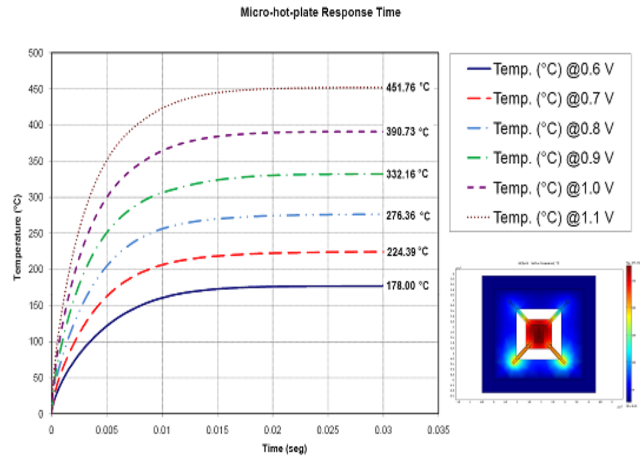

Fig. 7. Transient response of the microhot plate with different voltages applied.

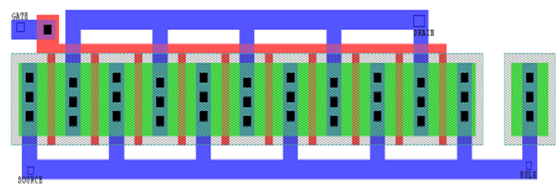

Fig. 8. Power MOSFET used in the control circuit, W/L=120µm/1.6µm.

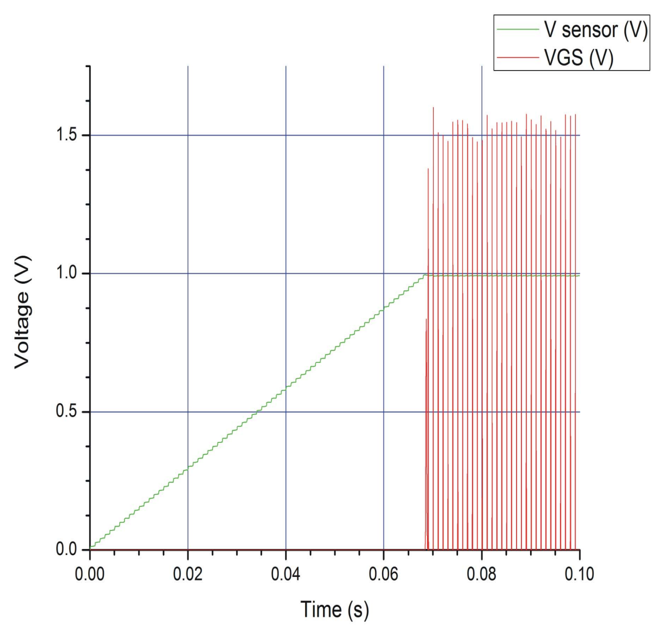

Fig. 9. Equivalent control circuit simulation results.

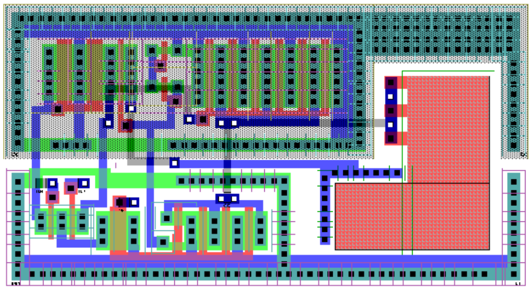

Fig. 10. Op-amp layout.

After simulating the original circuit, the results show how the transistor changes states when the voltages at the op-amp inputs are the same. This indicates that the control system works correctly as the microhotplate heats up and cools down. Fig. 11 shows the voltage at the gate of the transistor and the voltage at the sensor. When the latter rises to the reference voltage, the former goes from high to low, opening the heater circuit.

Fig. 12 shows a micro-photograph of the chip sent for fabrication. It contains the control system, a reading circuit and preparation for the micromachining of the micro hotplate. There are also some test structures for characterization purposes.

VI. Conclusions

From the previous results, it was established that a sensor prototype can be designed in a small silicon area that includes circuitry and sensor within the same chip. PSPICE simulations show that the proposed circuit has a low power consumption (2mW at 1.5V), useful for portable gas detection systems. A simple control loop can manage the microhotplate heating system. It was shown that the integration of the microheater and temperature sensor can be made with the same polysilicon layer, offered by standard CMOS technology.

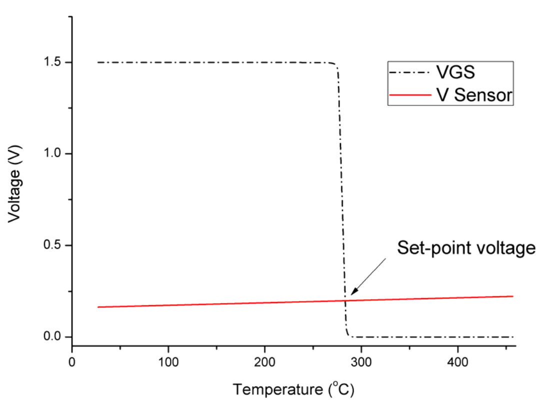

Fig. 11. State change at MOSFET's gate.

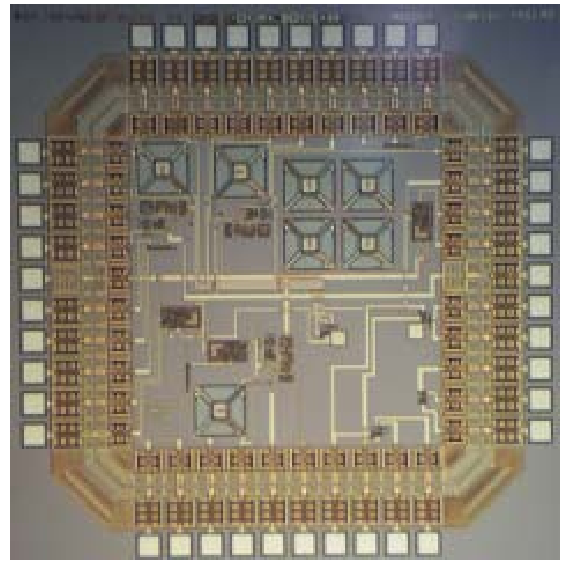

Fig. 12. Micro-photograph of the fabricated circuit.

Acknowledgment

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