Floating Gate MOSFET Circuit Design For a Monolithic MEMS GAS Sensor

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ABSTRACT
Gas sensors based on various principles and configurations have been studied for several years. Some of them are based on resistance variation of sensing layers. On the other hand, floating-gate MOSFETs can modify its threshold voltage by means of a chemical reaction. Here a study is made to prove that the charge produced by such chemical reaction can affect the voltage upon the floating gate. An analysis of a reading circuit with an FG-MOS as the transducer is made, showing this approximation as a promising alternative for gas sensors. A very simple design can be made for fabrication of a monolithic gas sensing system, by using a standard technology, supported in a MEMS structure for thermal isolation purposes. In order to show feasibility of this idea, experimental data is obtained using a conventional MOSFET and an Fe_2O_3 layer, showing that the system can be used as a gas sensor.

Categories and Subject Descriptors
J.2 [**Physical Sciences and Engineering**]: *electronics, engineering.*

General Terms
Design and Measurement.

Keywords
MEMS, Gas sensor, FGMOS.

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1. INTRODUCTION
Gas sensor structures using metal oxides as sensing layers are widely used for very diverse applications. Depending on the sensitive layer used, organic or inorganic gases can be detected [1, 2]. Commonly, the resistance variation of these layers is used to correlate this parameter with gas concentration [3]. Here we show that a Floating-gate MOSFET (FG-MOSFET) can be used as a transducer for gas detection by taking advantage of the charge derived from the chemical reaction between either reducing or oxidizing gases and a sensing layer, like metal oxides, causing a threshold voltage shift of the MOSFET. This principle has been applied in pH meters of liquid solutions by using a non-standard technology [4, 5]. Our work suggests a structure that can be designed and fabricated by using standard CMOS technology compatible with MEMS, in conjunction with an anisotropic etching post-process of the chip. In this design, semiconducting metal oxides heated to temperatures up to 400°C can be used without affecting the circuitry performance. In order to assess the possibility for using the principle described above, simulations of a circuit that uses an FG-MOS as the transducer, were carried out, assuming different charge magnitudes present upon the floating-gate of the transistor. The transference function shift of the simple amplifier used as the reading stage was the result of the threshold voltage shift due to the presence of charge exchange between the atmosphere and an appropriate layer, sensitive enough to the gas of interest. Similarly to what happens in electrochemical cells, when a convenient redox reaction takes place due to the gas-surface interaction, some electronic charge is transferred and a certain voltage is produced as a consequence of this charge transfer. This voltage is given by the Nernst equation [6, 7]. Therefore a potential can be added/subtracted to/from the floating gate, whose magnitude depends on the concentration of the reacting species. By using an equivalent circuit with a conventional MOSFET and an iron oxide-pyrrole film as the sensing element, a simple experimental illustration of this phenomenon is shown.

1.1 Mechanisms for the modification of charge upon the floating-gate of a MOSFET

Several mechanisms to inject/extract charge to/from the floating-gate of an FG-MOS are known, like hot electron injection, Fowler-Nordheim tunneling and direct tunneling. An electric field must be present to promote this injection/extraction. The magnitude of the charge injected/extracted depends on the magnitude of the electric field, and is self-limited. This charge will remain unaffected until a larger or an inverted electric field is applied. Depending on the polarity of the charge, the threshold voltage of the FG-MOS shifts to the right or to the left in a transconductance curve. This principle was used in pH meters (Ion Sensitive Field Effect Transistor: ISFETs), where a "floating gate" was used to interact with solutions. The system reported was used only for solutions and was not fabricated with standard technologies. Gases reacting with specific elements can also be considered as a source of charge, since a chemical reaction can give free electrons or ions as a byproduct. Then the possibility arises to correlate the gas concentration with the amount of threshold voltage shifting. Besides, standard technologies are available that offer the facility to design and fabricate MOS transistors with a real floating gate using two polysilicon layers, which is not the case of known ISFETs.

1.2 Charge and chemical reactions

When oxygen is adsorbed on the surface of a metal-oxide layer, it dissociates forming O^- and also an electron is extracted from the layer as shown in Eq. 1. If a reducing gas like hydrogen is present in the ambient, it reacts with the adsorbed O^- giving water as a byproduct and an electron is re-injected (Eq. 2). This is a model used to explain the resistance variation of the metal-oxide layer, but also shows that charge exchange is present due to the chemical reaction. So, if this charge exchange is present, the threshold voltage of the FG-MOSFET should be affected. Then, this kind of chemical reaction can be considered as another way for injecting/extracting charge to a floating gate if the FG-MOSFET is conveniently designed. It is important to say that in most cases temperatures above 200°C should be present to make these reactions happen. Eq. 3 considers the case for the presence of an oxidizing gas in the atmosphere, like carbon monoxide. A free electron is produced, exchanging charge as well.

$$\mathrm{O}_2 + 2e^- \rightarrow 2\mathrm{O}^- \tag{1}$$

$$\mathrm{H}_2 + \mathrm{O}^- \rightarrow \mathrm{H}_2\mathrm{O} + e^- \tag{2}$$

$$\mathrm{CO} + \mathrm{O}^- \rightarrow \mathrm{CO}_2 + e^- \tag{3}$$

Measurement of pH solutions with ISFETs is based on the thermodynamic principle described by the Nernst´s equation. Thus an analysis was conducted by simulating first the operation of an FG-MOSFET fabricated with standard technology, considering different voltages upon the floating gate due to a reaction between a heated semiconducting metal-oxide layer and a gas. Fig. 1 shows the suggested structure for a gas sensor using an FG-MOSFET fabricated with standard CMOS technology.

1.3 Thermal isolation in the monolithic system.

Equations 2 and 3 take place at high temperature, commonly within the range 200°C - 350°C. In order to locally heat the sensing area in the integrated circuit, structures as micro-hot-plates [8, 9, 10, 11], can be designed and integrated in standard technology with a micro-heater based on polysilicon. The purpose is to integrate a monolithic system with the sensing structure, the temperature control and signal processing circuitry. To thermally isolate the micro-hot-plate from the substrate, the polysilicon heater and the sensing elements are located in a MEMS suspended membrane. It is made by a post-process etching method; using a TMAH (Tetramethyl Ammonium Hydroxide) solution that is highly compatible with the layers used in standard technology, since practically does not attack aluminum, silicon dioxide and silicon nitride. After etching, a microcavity is present below the membrane containing the heater and the sensor, effectively isolating the substrate from the heat source.

2. MODELING, SIMULATIONS AND EXPERIMENTS

Analysis of the thermal behavior of the micro-hot-plate and the electrical response of the reading circuit was carried out to confirm the hypothesis proposed. The modeling, simulations and experiments from each one are briefly summarized.

2.1 Modeling and Simulation of the micro-hot-plate.

The thermal-electrical analysis of this structure was made with COMSOL Multiphysics, by coupling the thermal an electrical performance of the micro-heater, the sensor and the microcavity. The micro-heater is simply a resistor made of polysilicon; when a voltage is applied to its terminals, the Joule effect will heat the resistance. Thus, depending on the current density, a resistance variation owing to the heating will result, with a corresponding temperature rise. Using this thermally modified resistance property of the polysilicon, another resistor (also made with polysilicon) is placed near the heater, acting as a temperature sensor for the control circuit. Above this first polysilicon layer, there is a second polysilicon layer separated each other with silicon dioxide that is connected to the floating gate of a MOS transistor through an aluminum strip (see Figure 1).

This last polysilicon layer will be covered with a metal-oxide film that will be deposited as a post-process. Using an integrated temperature control circuit, the desired high temperature can be set in the sensing layer and the reaction between the gas and the layer should take place. Simulations were carried out with a voltage range applied to the micro-heater from 0V to 1.1V and Figure 2a shows the simulation results with 0.8V applied to the heater, reaching a temperature of 277°C. It can be seen that the cavity walls (clear figures) are isolated from the heat, the temperature is almost evenly distributed on the membrane area and the sensor temperature is the same as the heater. Figure 2b shows the response time to 0.8V applied to the heater, which turns out approximately 20 ms.

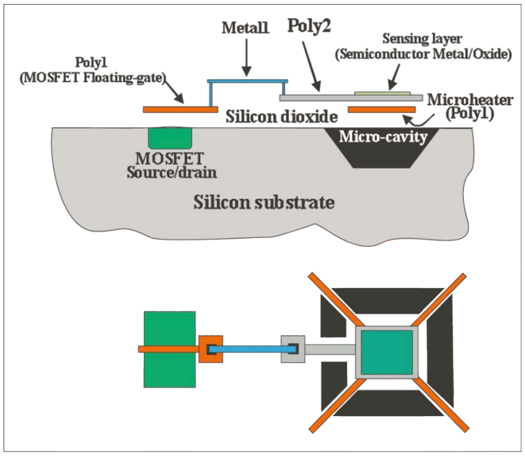
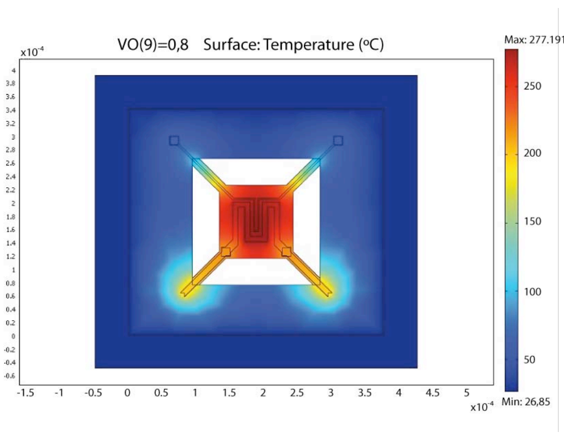
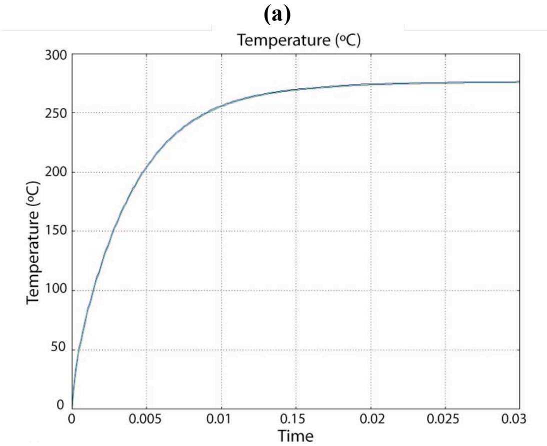


Figure 1. Proposed structure for the fabrication of a gas sensor based on an FG-MOSFET.



(a)



(b)

Figure 2. a) Micro-hot-plate heating at 0.8V; b) response time of the micro-hot-plate.

2.2 Reading circuit.

Following, an analysis is presented of the expected threshold voltage shift due to the charge present in the floating-gate, as a consequence of the presence of the measured gas. PSPICE was used to simulate the behavior of an FG-MOSFET with the dimensions projected for a prototype of a gas sensor system, with the assumption that a potential is present at the floating gate, as can be predicted from Equations 1 and 2. Since this potential is unknown until practical measurements can be done, possible induced voltages are arbitrarily proposed to obtain a plot where the behavior of the floating gate/sensing structure layer can be predicted. The simulation of a two-input FG-MOS with variation of the charge in the floating gate effectively shows this behavior. The results are shown in Figure 3.

For the reading circuit, a current mirror can be used for the gas sensor using an FG-MOSFET as a load and a common source output amplifier, as shown in Figure 4a. The basic idea behind this circuit is to compare the gate voltages of M1 and M2 from Figure 4a.

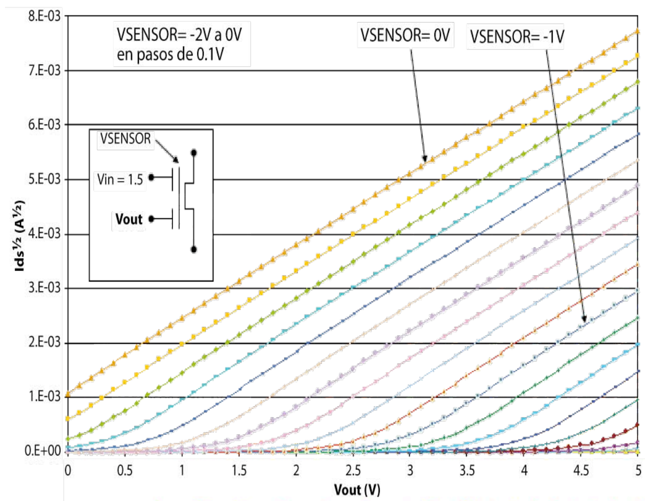
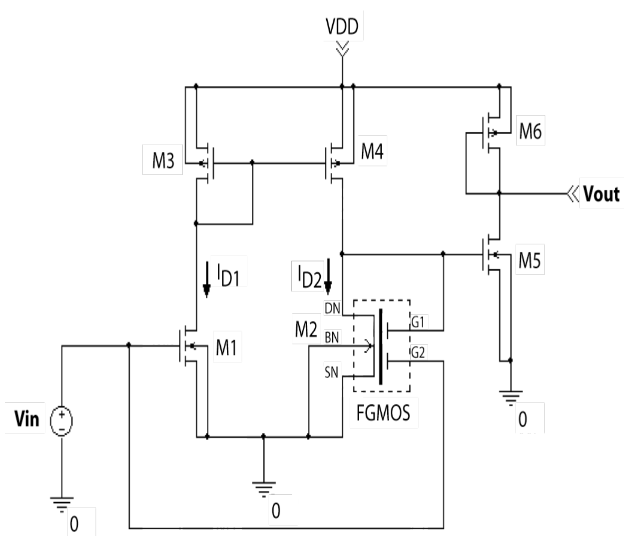
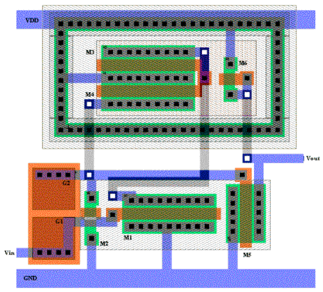


Figure 3. PSPICE simulation of an FG-MOS with charge in the floating gate



(a)



(b)

Figure 4. (a) Reading circuit for the gas sensor (b) Layout

These transistors have the same aspect ratio, so, if the drain current through both transistors is the same, the gate voltage will be the same as well. A relation can be obtained between the drain voltage of the FG-MOS and the stored charge. From Figure 4a, it can be seen that this voltage will be the input signal for the common source amplifier. The gate voltage of M1 sets the operating point of the reading circuit for a less distorted output signal and with the highest gain.

The highly amplified signal shows the good performance of the reading circuit. This is a rather simple amplifier configuration that can be improved for higher gain and S/N ratio, but is enough to simply demonstrate the feasibility of the FG-MOS as a gas sensor, with the possibility to be integrated with standard technology. After getting these results, indication shall be given that the hypothesis stated above can be successful. A simple experiment explained ahead will help to confirm these simulations. Although a discrete transistor is used, it should be clear that the configuration is a macro-scale system of what can be integrated as proposed in Figure 1. Clearly, in the experimental setup used in the test, the gate voltage can be directly measured, being a task that cannot be done with an FG-MOS. Finally, the output voltage measurement is made in the same way in both configurations described. Hence, the experimental setup is a hybrid version of the monolithic integrated version.

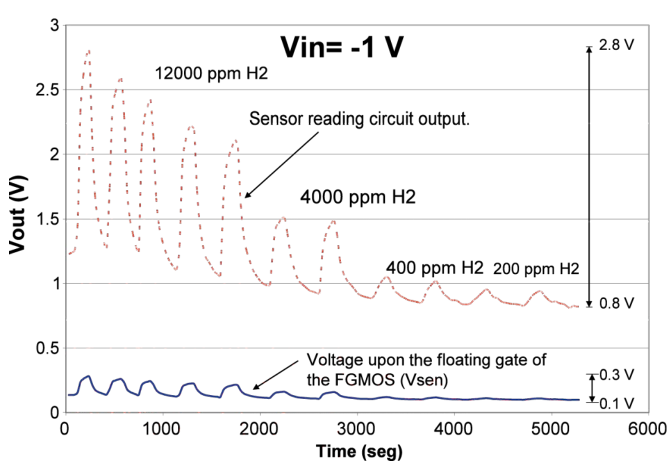


Figure 5. Input sensor signal Vsen and reading circuit output, Vout.

3. EXPERIMENTAL RESULTS USING A CONVENTIONAL MOSFET

An experimental amplifier setup was implemented with a conventional MOSFET, connecting a layer of Fe_2O_3 grown over a glass substrate, to the gate of this device. Only the layer was placed inside a chamber with controlled temperature and atmosphere and a simple amplifier was configured and placed outside the chamber, so its output voltage can be read while a known flow of propane was passed through the chamber. Prior to this test, a simulation of a similar amplifier setup was done, but considering an FG-MOS instead of the conventional MOSFET. Figure 5 shows the response plot of the circuit in Figure 4a, with an arbitrary voltage signal, simulating the electrochemical potential due to a chemical reaction upon the floating gate, Vsen, considering different gas concentrations.

Figure 7 shows the transfer function resulting after simulating the amplifier in Figure 6. The figure inset shows the different values given to Vsen, where negative and positive voltages where explored, since the polarity of the potential produced by the chemical reaction is also unknown. The shift direction of the transfer curve as a function of the polarity of Vsen can be clearly determined. From the figure it can be seen that the curve shifts to the left of the equilibrium signal (Vsen = 0V, no chemical reaction) for positive Vsen voltages, otherwise the shift is to the right. It is important to point out that these curves are useful to choose the operating point of the amplifier so a reliable output voltage can be read, in order to use the high gain region of the transfer curve when the FG-MOSFET is in a saturation regime. A DC analysis is enough to consider the behavior of the system, since in practical situations the amount of gas reacting with the layer is not expected to vary quickly in time.

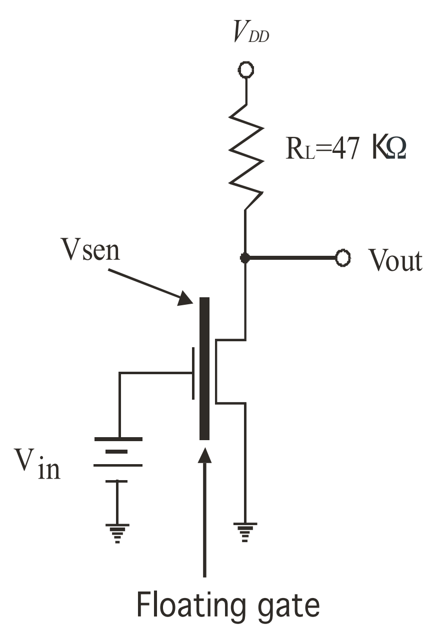


Figure 6. Amplifier simulated with an FG-MOS

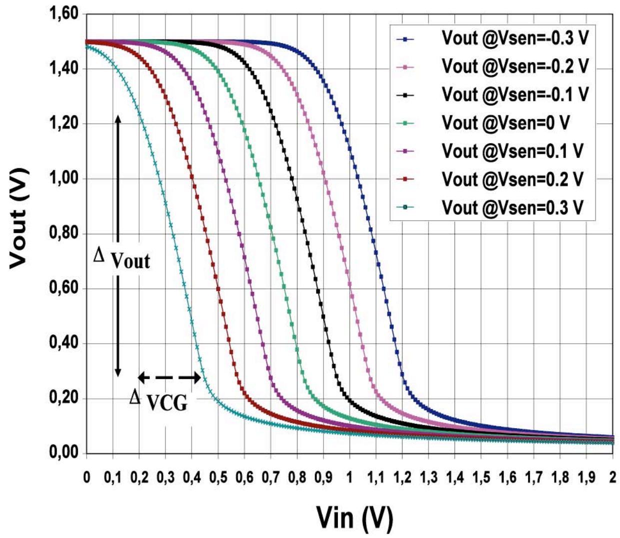


Figure 7. Transfer function with gas interaction of a sensing layer in contact with the floating gate of an FG-MOSFET.

3.1 Model validation with a conventional MOSFET.

An experimental amplifier setup with a conventional MOSFET was used to prove the feasibility of the method proposed to measure the electrochemical voltage induced by a chemical reaction (Figure 8). An MOS transistor was used with a 47 kΩ load resistor and a bias voltage of V_{DD} = 5V. The layer of Fe_2O_3 (hematite) mixed with pyrrole was kept at 30°C inside the experimental chamber in the presence of 50% of humidity to detect several concentrations of propane.

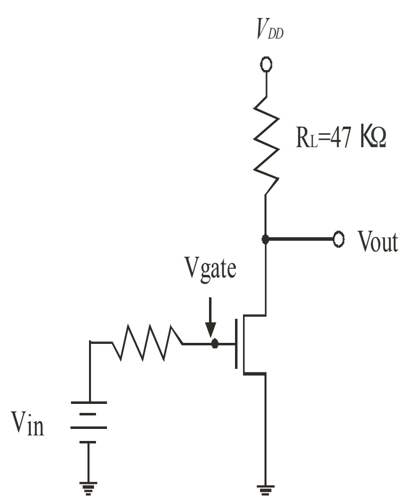


Figure 8. Experimental amplifier configuration

The experimental results are shown in Figure 9; the resistor connected in series with the Vin bias source in Figure 8 represents the sensing layer. Regularly, this sensing layer has a high resistance either before or after the interaction with a gas. Also, the resistance of the MOS gate is very high. This avoids leakage currents and assures a correct measurement of the voltage present in the sensing layer when the chemical reaction is taking place. The transfer curve with Vsen = 0V has its high gain region between 1.7V and 2V of Vin. It can be seen that a negative potential is created due to the chemical reaction. Good resolution in the output voltage readings was obtained for propane concentrations of 250 ppm and 500 ppm.

From Figure 8 it is clear that the voltage drop on the sensing layer is given by the difference between the voltage read at the MOSFET gate and the Vin voltage, as follows:

$$Vsen = Vgate - Vin\,, \tag{4}$$

where Vgate is the MOSFET gate voltage referenced to ground. Since the output voltage, Vout, depends on the amplifier's gain, it is advisable to take the Vgate reading of the circuit at the higher gain operating point, Vout=1.65V in this case (see Figure 9). With this output voltage for the maximum amplifier gain, the electrochemical potentials are: -2.824V for 0 ppm + 50 % humidity, -4.33V for 250ppm + 50 % humidity and -10.53V for 500ppm + 50 % humidity.

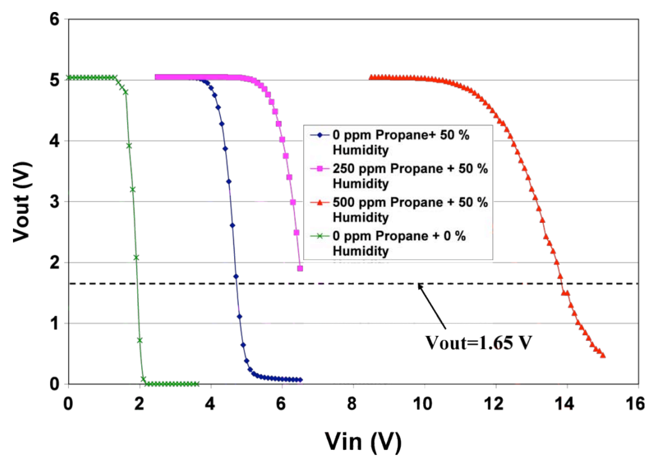


Figure 9. Gas measurements, using a conventional MOSFET, in the presence of different propane concentrations with 50 % humidity.

Noticeably different voltages were obtained as a consequence of the chemical reaction of the Fe_2O_3 film with propane. For the amplifier using the conventional MOSFET, measuring Vgate and using equation 4, is enough to deduce the electrochemical potential. This cannot be done if an FG-MOSFET is used, since there is no way to directly read the potential of the floating gate. Therefore, an indirect method must be used to achieve this task. The next section shows the way this could be done.

3.2 Extrapolation to a gas sensor with an FG-MOSFET.

Based on Figure 6, it can easily be shown that:

$$Vout = G * Vin + Vsen\,, \tag{5}$$

where G is the gain of the amplifier. Once again, using the operating point where the amplifier has its higher gain, and reading its corresponding Vout, then Vsen can be determined as well, for a sensor structure based on an FG-MOSFET. From Figure 7: Gmax=0.8, Vout @ Gmax=0.6 V. Then, reading the operating point for each curve in the graph, effectively results in the supposed voltages in the floating gate, proving that equation 5 and the method used, are reliable.

4. CONCLUSIONS

A whole system that integrates the FG-MOSFET based sensor with the associated electronics can be designed based on the threshold voltage shift caused by the interaction between the measured gas and the metal-oxide layer connected with the Floating-gate of an FG-MOS, instead of the layer resistance variation, as is used in conductometric gas sensors. As described, the fabrication of this system is based on the compatibility of post-processes with standard CMOS technology. This gives the opportunity to improve the design for different purposes, as different sensitive layers, reading circuit configurations and MEMS structures can be conceived and configured.

5. ACKNOWLEDGMENTS

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