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Analysis of the potential upon the floating gate of an FGMOSFET used as a gas sensor

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Gas sensor structures using metal oxides as sensing layers are widely used, but commonly the resistance variation of these layers is used to correlate this parameter with gas concentration. Here, we show that the sensitivity of a Floating-gate MOSFET (FGMOSFET) can be used also in gas detection by taking advantage of those ions derived from the chemical reaction between either reducing or oxidizing gases and a sensing layer, like metal oxides. This principle has been used in pH meter of solutions but by using a non-standard technology. This work suggests a structure that can be designed and fabricated by using standard CMOS technology. It should be stressed that this technology is compatible with MEMS. In this design, semiconducting metal oxides heated to temperatures up to 400 °C can be used. In order to assess such a possibility, the results from an equivalent circuit using a conventional MOSFET and an iron oxide-pyrrole film as the sensing element are shown.

Keywords: FGMOSFET; Gas sensors; MEMS; Metal-oxides

1. Introduction

Gas sensors have been studied since several years ago and are in continuous development based on different principles and configurations. Also, the applications of this kind of sensors are very diverse, because depending on the type of sensitive layer used, compounds as organic or inorganic gases can be detected, such as methane (CH_4), hydrogen (H_2), carbon monoxide (CO), nitrogen dioxide (NO_2) or even odor and aroma of food, for instance [1,2,3,4,5]. Several transduction methods are used for gas sensors, some important cases being for instance the resistive and Surface Acoustic Wave (SAW) devices [6]. In this work, an analysis of a different operation mode is made, which takes advantage of the threshold voltage shift of MOSFET devices. In particular, this analysis is based on the floating-gate MOSFET's and the effect upon it that should be caused when a chemical reaction takes place between a sensing layer connected to the floating gate and either a reducing or oxidizing gas. Such sensors are already used, but only for determination of solution's pH, not for gases [7,8,9]. Furthermore, they are fabricated with non-standard technologies. This last point is very important, since in industry the trend is to lower the fabrication costs of sensors, using standard technologies, for instance. It is well known that the threshold voltage of MOSFETs depends on any charge present in the gate or the $Si\text{-}SiO_2$ interface. Any increase or decrease of this charge will be reflected on the threshold voltage shift. This effect is already used in FGMOSFET based non-volatile memory devices throughout injection of charge to the floating gate. The same effect can be achieved by another method that has not been reported, regarding the modification of charge in the floating gate of CMOS FGMOSFETs. This can be achieved when a metal-oxide layer is exposed to air. Here, oxygen is adsorbed on the surface and dissociates forming O^-, also an electron is extracted from the layer (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 shows also that charge exchange is present due to the chemical reaction. This charge exchange can be detected by the floating gate of the FGMOSFET, throughout a shift of its threshold voltage.

$$O_2 + 2\boldsymbol{e}^- \rightarrow 2O^- \quad (1)$$

$$H_2 + O^- \rightarrow H_2O + \boldsymbol{e}^- \quad (2)$$

Eqs. (3) and (4) consider the case for the presence of an oxidizing gas in the atmosphere, like carbon monoxide. A free electron is produced, exchanging charge as well.

$$O_2 + 2e^- \rightarrow 2O^- \quad (3)$$

$$CO + O^- \rightarrow CO_2 + e^- \quad (4)$$

These equations are used to explain the variation of the surface resistance of the metal-oxide in sensors that use this principle in gas detection. It is important to say that in most cases, temperatures above 200 °C should be present to make these reactions to occur. As can be seen, if the layer is exposed to oxygen present in the environment, it dissociates as O^- and electrons are extracted from the layer, this is, the donor electrons in the crystal surface are transferred to the adsorbed oxygen. (The result is positive charge at the

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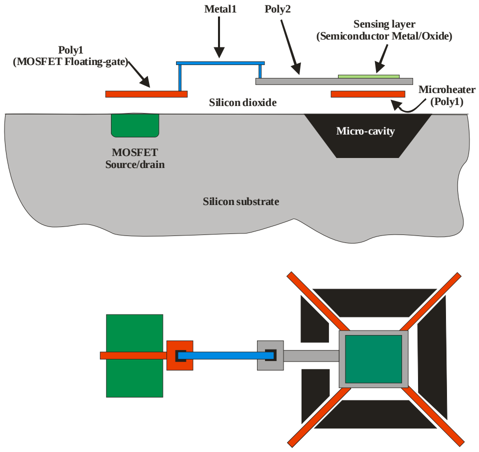

Figure 1. Proposed structure for the fabrication of a gas sensor based on an FGMOSFET.

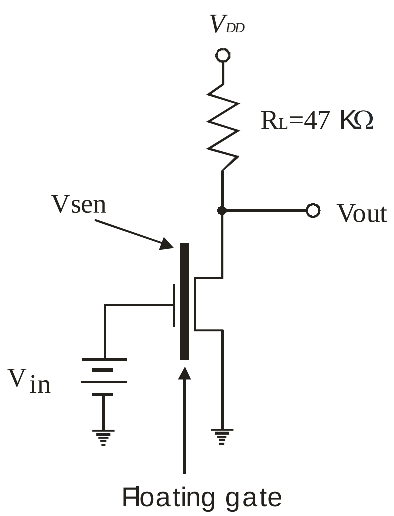

Figure 2. Amplifier used to model gas sensing with an FGMOSFET.

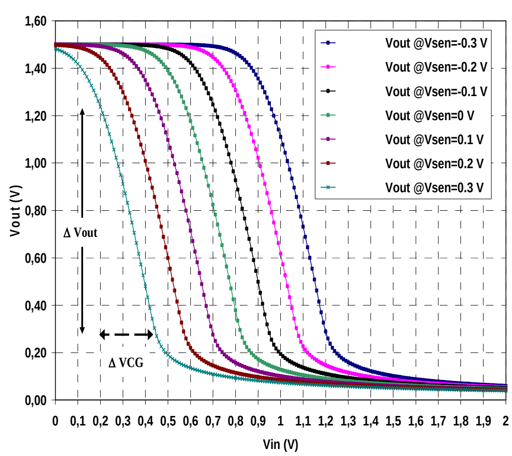

Figure 3. Transfer function of the amplifier used for the theoretical analysis of gas interaction of a sensing layer in contact with the floating gate of an FGMOSFET. Wn/Ln=12μm/1.6μm.

surface of the layer, creating a space charge layer acting as a barrier for current flow and an associated potential with a resistance decrease). When a reducing gas stream is then passed upon the metal-oxide layer (Eq. 2), the reaction with the adsorbed O^-, decreases the density of negatively charged oxygen, injecting electrons to the layer. This causes a resistance change and results in negative charge at the surface of the layer. Nernst equation considers this thermodynamic principle and is the one used with ISFET (Ion Sensitive Field Effect Transistor) to measure pH of solutions. Then, based on this principle, the following analysis is made to study the operation of an FGMOSFET fabricated with standard technology, with charge induced upon the floating gate due to the reaction between a heated semiconducting metal-oxide layer and a gas. Fig. 1 shows the suggested structure for a gas sensor using an FGMOSFET fabricated with standard CMOS technology. In order to assess such principle previous to the implementation of the structure in Fig. 1, an experiment using a separate MOSFET and sensitive layer setup, in the presence of propane was carried out.

2. Model for an FGMOSFET sensor

First of all, a simulation based on an FGMOSFET with the dimensions projected for a prototype of a gas sensor system was performed. PSPICE was used to simulate the behavior of this device, 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, magnitudes of the possible voltages induced are arbitrarily proposed to obtain a graph where the behavior of the structure floating gate/sensing layer can be predicted. An appropriate model for the FGMOSFET was used, where the dimensions of the channel width and length, and the coupling capacitance between control gate (Poly2) and floating gate (Poly1) are known [10]. Fig. 2 shows the basic amplifier used in the simulation, from where the output voltage (Vout) vs control gate voltage (Vin) behavior, with the voltage due to the chemical reaction (Vsens) as a parameter, can be obtained.

Having in mind one of the main objectives for portable gas sensor systems, as low power consumption, a bias voltage V_{DD} = 1.5 V was chosen. An amplifier load resistance of 47 KΩ gives a relative good gain for such a simple amplifier; a voltage sweep for Vin from 0 V to 1.5 V is used as the independent variable and finally, the parameter Vsen varies from -0.3 V to 0.3 V, with 0.1 V steps.

3. Results and discussion

Fig. 3 shows the transfer function calculated for the amplifier in Fig. 2. The figure inset shows the different values given to V_{sen}, where negative and positive voltages where explored, since the polarity of the potential produced by the chemical reaction is also unknown. So, the sign of the shift of the transfer curve as a function of V_{sen} polarity, can be

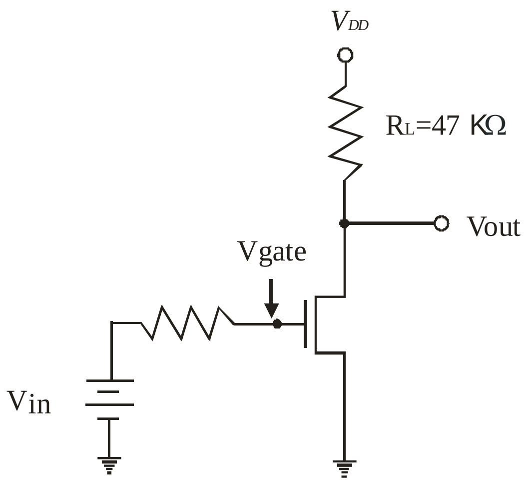

Figure 4. Experimental amplifier configuration, using a conventional MOSFET.

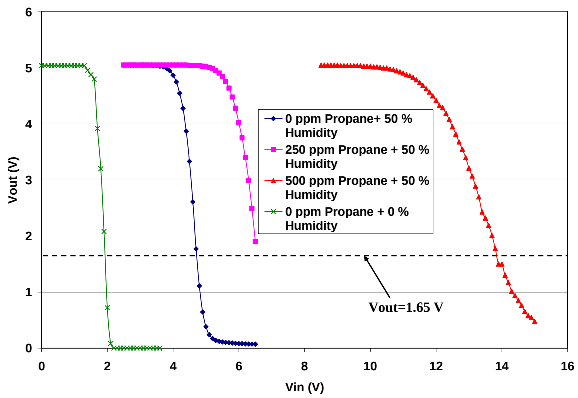

Figure 5. Experimental transfer functions, as a result of chemical reaction of the sensing layer with propane, in the presence of 50 % of humidity inside the test chamber.

Table 1. Voltages in the fe_3o_2 sensing layer, due to the chemical reaction with propane.

Concentration of Propane	**Vgate** (V)	**Vin** (V)	**Vsen** (V) @ Vout=1.65 V
0 ppm (considering zero resistance of the sensing layer)	1.976	1.976	0
0 ppm + 50 % humidity	1.976	4.8	-2.824
250 ppm + 50 % humidity	1.97	6.3	-4.33
500 ppm + 50 % humidity	1.97	12.5	-10.53

clearly determined. Then, from the figure it can be seen that the curve shifts to the left of the equilibrium signal (Vsen=0, no chemical reaction) for positive V_{sen} voltages, otherwise the shift is to the right. It is important to point out that these curves are useful also to choose the operating point of the amplifier so a reliable output voltage can be read. For example, suppose that a V_{sen} = 0.3 V is induced upon the floating gate (see Fig. 3). Then, in order to use the high gain region of the transfer curve, the Vin value should be varied approximately between 0.2 V and 0.45 V, since in this range the FGMOSFET is in the saturation region. This range gives values for V_{out} between 1.24 V and 0.27 V, respectively. But if Vin is lower than 0.2 V or higher than 0.45 V, low gains will result from the amplifier and the device will not be operating in the saturation region.

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 too much in time.

a) Model validation with a conventional MOSFET

An amplifier set with a conventional MOSFET was used to prove the feasibility of the method proposed to measure the electrochemical voltage induced by a chemical reaction, so it can be extrapolated to an FGMOSFET. An MOS transistor was used with a 47 kΩ load resistance and a bias voltage of V_{DD} = 5 V. Fig. 4 shows the configuration, where the resistance connected in series with the Vin bias source represents the sensing layer. Regularly, this sensing layer –that can be any of the different layers with diverse materials reported in the literature–, has a high resistance either before or after the interaction with a gas. Also, the gate 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.

A layer of Fe_2O_3 (hematite) mixed with pyrrole was used to measure the electrochemical potential created by its chemical reaction with propane in the presence of 50 % of humidity in the experimental chamber. The layer was kept at 30 °C. The results are presented in Fig. 5. The transfer curve with Vsen = 0 V has its high gain region between 1.7 V and 2 V of Vin. It can be seen that a negative potential is created due to the chemical reaction between the layer and a known concentration of propane, in the presence of 50 % of humidity. Good resolution in the voltage readings was obtained for propane concentrations of 250 ppm and 500 ppm. From Fig. 4 it is clear that the voltage on the sensing layer is given by the difference between the voltage read at the MOSFET gate and the Vin voltage, as follows:

$$\text{Vsen} = \text{Vgate} - \text{Vin}\,, \qquad (5)$$

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 = 1.65 V in this case (see Fig. 5). Table 1 shows the electrochemical potential derived due to the chemical reaction between the film and propane.

As can be seen in Table 1, noticeably different voltages were obtained as a consequence of the chemical reaction of the hematite film with propane. This is valid for 0 ppm, 250 ppm and 500 ppm of propane. These results suggest that interesting work could be done by designing a whole system that integrate the sensor with the electronics, based on FGMOSFETs. It would detect the threshold voltage shift instead of the layer resistance variation, as is used in conductometric gas sensors [11,12,13,14,15,16]. For the amplifier using the conventional MOSFET, by measuring Vgate and using equation (5), is enough to deduce the electrochemical potential. This can not be done if an FGMOSFET 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.

b) Extrapolation to a gas sensor with an FGMOSFET

Based on Fig. 3, it can easily be shown that:

$$\mathrm{Vout} = \mathrm{G} * \mathrm{Vin} + \mathrm{Vsen}, \qquad (6)$$

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, Vsen can be determined, as well, for a sensor structure based on an FGMOSFET. From Fig. 3: 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 (6) and the method used, is reliable. The purpose is to use CMOS technology compatible for MEMS structures, using post-processing, reported elsewhere [17], for micromachining a membrane that contains the microhot plate. The design must allow heating the layer even up to 400 °C, and to take advantage of the micromachining for thermal isolation purposes. This point is very important for isolating this sensor's temperature from the substrate containing the signal processing electronics, giving the chance of being constructed monolithically.

4. Conclusion

It was demonstrated that the potential created upon the floating gate of an FGMOSFET, due to the chemical reaction between a reducing or oxidizing gas and a semiconducting metal oxide, can be measured with a simple amplifier set. This is the electromotive force created in a spontaneous reaction predicted by the Nernst equation. The operating principle can be used toward the design of a gas sensor using an FGMOSFET and was proved through an amplifier configuration using a conventional MOSFET. The importance of this proposal is supported by the possibility to fabricate a gas sensor based in standard CMOS technology compatible with MEMS. This may allow the design of a sensor that operates at high temperatures, along with the signal processing electronics, since the sensor structure can be thermally isolated by a micromachining underneath it, without affecting the operation of the electronic circuit. The measurements made, show good resolution for propane concentrations between 0 ppm and 500 ppm. This suggests that advantage can be taken on, using the threshold voltage shift for gas sensing. In order to characterize other kind of layers that could generate positive voltages, based either in polymers or metal oxides, work should be done. Usage of MEMS provides freedom in the operating layer temperature, that can be either low or high depending on the kind of layer material and its thermodynamic needs for the reaction with a gas.

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