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GAS SENSORS BASED ON SILICON CARBIDE MOS CAPACITOR

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Rezumat. *În acest articol se prezintă o sinteză dedicată capacitorului MOS pe carbură de siliciu şi aplicaţiilor sale ca senzor de gaze. Sunt descrise modurile de operare ale capacitorului şi caracteristica capacitate-tensiune (C-V) ideală. De asemenea, este investigat efectul sarcinilor din interiorul oxidului şi de la interfaţa oxid-semiconductor asupra curbei C-V. Capacitoarele MOS sunt folosite în special ca senzori de gaz. În cazul în care semiconductorul este carbura de siliciu (*SiC*), atunci senzorul poate fi utilizat şi în medii ostile, la temperaturi mari. Capacitoarele* SiC *MOS pot detecta hidrogen şi diferiţi compuşi ai acestuia. Mecanismul de detecţie este detaliat în lucrare in două cazuri: la temperaturi joase şi respectiv la temperaturi înalte. Se prezintă reacţiile chimice care au loc atunci când senzorul este introdus în două medii: numai în hidrogen şi, respectiv, în hidrogen cu oxigen. La temperaturi mici, interacţiunea cu gazul modifică lucrul mecanic de extracţie din metal, care determină deplasarea caracteristicii C-V. La temperaturi mari, curba C-V se deplasează de asemenea. În plus, forma sa este modificată de acţiunea sarcinilor electrice de la interfaţa oxid-semiconductor. În continuare, se prezintă un exemplu de senzor MOS de hidrogen pe carbură de siliciu, ce a fost fabricat şi caracterizat. Metalul structurii este* Pt, *oxidul este* SiO_2, *semiconductorul este* 6H-SiC *de tip n. Senzorul a fost testat într-un mediu ce conţine hidrogen şi în altul cu hidrogen şi oxigen, la* 800 K. *In fiecare caz se obţine curba C-V şi se analizează efectele gazelor detectate şi ale sarcinilor de la interfaţa oxid-semiconductor asupra acestei caracteristici. În final, se specifică, în mod concis, avantajele şi limitele folosirii capacitorului* SiC *MOS ca senzor de gaze.*

Abstract. *State of the art on silicon carbide MOS capacitor sensors is presented. The MOS on silicon carbide (SiC) is used for gas sensing in automotive exhausts, because the large band gap of SiC allows high temperature operation up to* 1200 K *in chemically reactive environments. The capacitance-voltage characteristics of* SiC *MOS structure and the effect of the oxide trapped charges are analyzed. Furthermore, the applications of the MOS capacitor were specified and the hydrogen sensor function was chosen for a detailed presentation. The mechanisms which explain the sensor response to hydrogen containing species is evinced: the chemical modification of the barrier height at the metal-insulator interface and the creation/passivation of charged states at the insulator-silicon carbide interface. The MOS capacitor hydrogen sensor behavior into an atmosphere that contains oxygen is also investigated.*

Keywords: Silicon Carbide, MOS capacitor, hydrogen sensor

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1. Introduction

There is a need for gas sensors in the emissions control of automotive exhaust and flue gases, for both real time monitoring and feedback control. Typical operation conditions are high temperature, chemically reactive environments and low or varying oxygen concentrations. To extend the possible operation temperatures from **500 K** to above **1200 K**, silicon carbide (SiC) is used as the semiconductor instead of silicon, due to its larger band gap. In addition, SiC is chemically stable, making it well suited for sensing applications in harsh and reactive environments [1].

In this paper, a detailed presentation of the MOS capacitor on silicon carbide was developed. The sensor structure and sensing mechanism are described based on the MOS structure physics. Two detection mechanisms will be discussed. Until recently, the response of metal-insulator-silicon carbide structures to hydrogen containing species has been ascribed entirely to the chemically induced shift in the metal-insulator work function. This model of sensor response is based on measurements performed on silicon based MOS structures at temperatures below **500 K**. At high temperatures (above **700 K**) an additional mechanism, the reversible passivation/creation of charged states near the SiO_2-SiC interface contributes to the hydrogen sensitivity [1].

The dependence of capacitance on the voltage applied to the MOS structure in accumulation, depletion and inversion conditions is discussed. The effects of the oxide trapped charges are taken into account. An experimental MOS capacitor sensor is analyzed and improvement methods are specified. The detection performance of SiC MOS sensor in hydrogen only and hydrogen and oxygen environment respectively is proved.

2. SiC MOS Capacitor Structure

The MOS capacitor structure consists of three layers: metal, oxide and semiconductor. In the ideal MOS structure, the oxide layer prevents the transport of charges from the metal to the semiconductor and it stores no charges. Consequently, the oxide layer has an infinite resistivity. The MOS capacitor can be found in four operating conditions: flat band (equilibrium), accumulation, depletion and inversion.

The flat band condition occurs when no voltage is applied to the metal electrode. Accumulation condition appears when a negative bias is applied to the metal electrode (for a *p*-semiconductor). This bias attracts the majority positive carriers (holes) of the semiconductor to the semiconductor-oxide interface. The capacitance of the MOS structure consists of the capacitance of the oxide layer (C_{OX}) only.

Depletion condition takes place for a positive voltage on the metal electrode. This positive bias repels the holes in the semiconductor away from the oxide-semiconductor interface. Thus, a depletion region occurs at the interface. The capacitance of this depletion region (C_S) is in series with the oxide capacitance.

When the positive bias increases, the surface potential in the semiconductor reaches a critical value equal to twice of the Fermi level potential and a thin *n* inversion layer arises at the interface. A further increase in metal voltage produces no changes in the depletion layer width, but electrons concentration from inversion layer is improved. The depletion region capacitance reaches its minimum value ($C_{S,min}$) which corresponds to the minimum value of MOS structure capacitance (C_{INV}).

The variation of the MOS structure capacitance as a function of the voltage applied to the metal electrode is shown in Fig. 1.

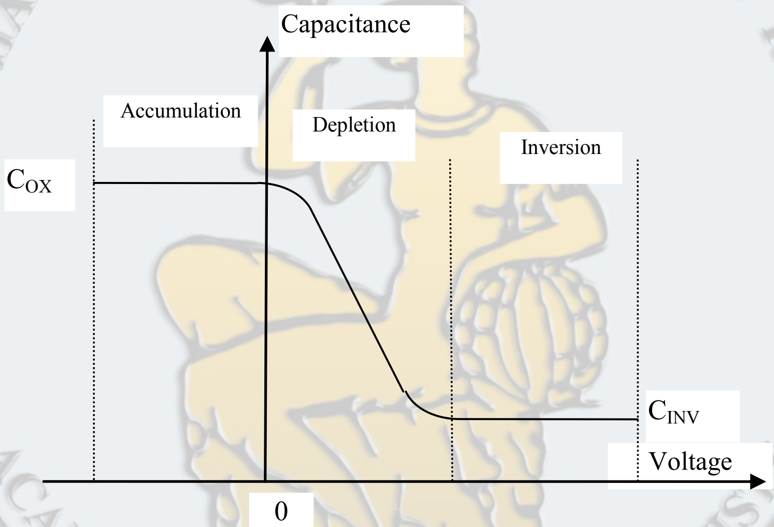

Fig. 1. MOS structure capacitance as a function of the voltage applied to the metal electrode.

The capacitance of MOS structure has a maximum value (C_{OX}). In the depletion region the MOS capacitance decreases as a function of voltage. This decrease is caused by the increase of the depletion region width, which reduces the capacitance of the depletion region. In the inversion region, the depletion region width increases very slow and it is considered to be stabilized at its maximum value. In this case the capacitance of the depletion region reaches its minimum value, thus MOS structure capacitance stabilizes at a minimum value (C_{INV}) [3].

In a real MOS structure, the flat band condition does not occur when there is no voltage applied to the metal electrode. This situation is caused by the charges trapped in the oxide layer, as shown in Fig. 2.

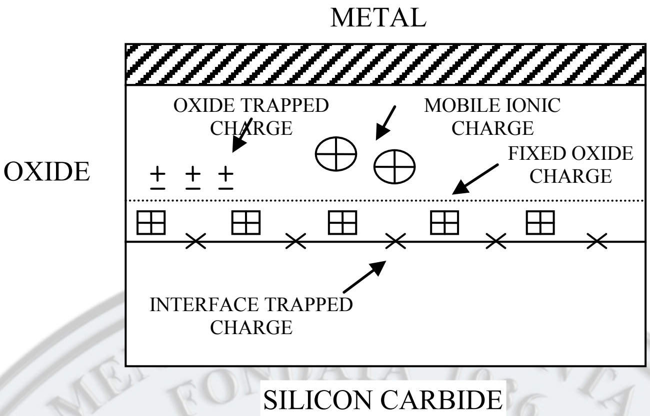

Fig. 2. Oxide trapped charges in MOS structure.

The oxide trapped charges include four types of charges: interface trapped state charges, fixed oxide charge, oxide trapped charge and mobile ionic charge [4].

The mobile ionic charge involves highly mobile ions of impurities, like sodium and potassium, which diffuse deeply into the oxide layer during device operation. The oxide trapped charge is given by the electrons and holes trapped in the bulk of the oxide layer. These carriers can result by radiation or high currents injected in the oxide layer. The fixed oxide charge is located in the oxide, near the interface with the silicon carbide layer and is caused by the incompletely oxidized oxide layer. This charge is not located at oxide semiconductor interface and is not modified during normal device operation [4].

These above mentioned three types of charges distributed inside the oxide are positive and create a depletion region at the surface of the *p*-type SiC semiconductor layer even at equilibrium. In order to obtain a flat band condition, a negative voltage must be applied to the metal electrode. This is the flat band voltage of the MOS capacitor (V_{FB}). Thus, the *C-V* characteristic of the real MOS capacitor shifts (to the left for a *p*-type semiconductor) with a value of V_{FB} from the ideal MOS capacitor *C-V* characteristic.

The interface trapped state charges are caused by the SiC – oxide interface defects. These imperfections can have one or more energy levels within the SiC band gap and exchange charge with SiC. The interface states in the lower half of the SiC band gap can interact with the valence band by capturing or emitting holes. They are donors and account for positive charges in *p*-SiC MOS structures. The interface states in the upper half of the SiC band gap can interact with the conduction band by capturing or emitting electrons. They are acceptors and account for negative charges in *n*-type SiC MOS capacitors. The capture or emission occurs when the voltage applied to the metal electrode changes [5].

The density of these electrically active centers is larger by at least two orders of magnitude in SiO_2–SiC interface (in the range of 10^{12} cm^{-2}) than in SiO_2–Si interface (in the range of 10^{10} cm^{-2}). There are two reasons for the higher interface states density in SiC. First, the band gap of silicon carbide is 2 to 3 times wider than that of Si, so additional energy levels in SiC band gap, over Si band gap, can be charged during device operation. Second, the number of defects in the SiO_2 layer grown on SiC is larger than in the one deposited on Si, even when considering only the Si band gap [6].

Interface trapped charge density changes when the voltage applied to the gate electrode is varied. An adjustment of the electrical charge in the depletion region of the semiconductor occurs for any voltage applied on the gate metal. This change is smaller in the presence of interface charge. Therefore, a lower band bending in silicon carbide is achieved. A larger gate bias voltage is required to drive the MOS capacitor from accumulation to inversion. Thus, the *C*-*V* characteristic of real MOS capacitor on silicon carbide is stretched out along the metal electrode voltage axis (Fig. 3) [5].

Fig. 3 shows the effect of oxide charges on the *p*-SiC MOS capacitor *C*-*V* characteristic. The fixed and mobile oxide charge produces a shift of the *C*-*V* characteristic to the left without modifying the curve shape. On the other hand, the interface trapped charge reveals an expansion of the *C*-*V* curve in the depletion region.

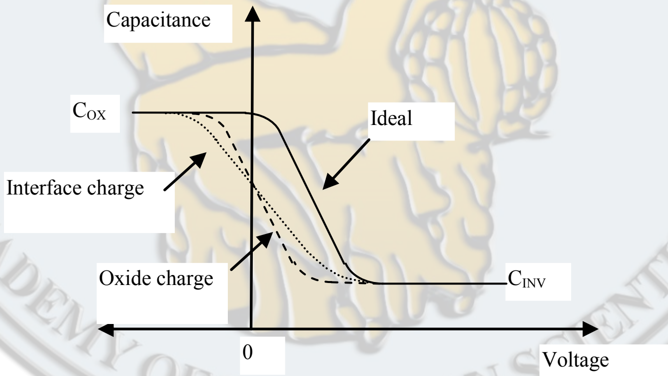

Fig. 3. Comparison of *C*-*V* characteristics of ideal and real MOS capacitor.

3. SiC MOS Capacitor Hydrogen Sensor

3.1. Introduction

MOS capacitors are widely used as gas sensors. If the semiconductor material of the MOS capacitor is silicon carbide, the gas sensor can be used in high temperature environments. This is due to the larger band gap of silicon carbide in comparison with silicon. The silicon carbide is stable in chemically reactive environments which makes it suitable for harsh environment applications. There are various applications for the MOS capacitor gas sensors. They can be used to detect the hydrogen sulfide in the interior of the volcanic vents [7] or the hydrogen, hydrocarbons, nitrogen and sulfur oxides in the automotive, food and energy sectors [8]. The SiC MOS capacitor sensors can also find volatile organic compounds [9]. The MOS capacitor can also be used as a nonvolatile memory element in computers [10].

The negative impact on the environment of conventional energy sources, like fossil fuels, has drawn attention to clean energy solutions. Hydrogen represents a clean energy source and there is a large interest in using hydrogen as an alternative energy source in many industries, such as chemical, petroleum, automotive and food [11].

Hydrocarbons contribute to the formation of greenhouse gases, too. They are found in the exhaust gases of the automobiles and also in the composition of plastics, solvents and pesticides. Hydrocarbons also produce health damage during short exposures.

Hence, there is a need for sensors that can detect hydrogen in different environments. The processes that involve hydrogen and hydrocarbons should be monitored and controlled. The sensors must be able to operate in high temperature and harsh environments for long periods of time and must have a better sensitivity than the smallest amount of hydrogen that could represent a danger [12]. In the following paragraphs, a hydrogen sensor based on silicon carbide MOS capacitor will be analyzed. The structure, sensing mechanism and electrical characterization of the sensor will be detailed.

3.2. Structure

The structure of a MOS capacitor gas sensor based on a *n*-type 6H-SiC is illustrated in Fig. 4.

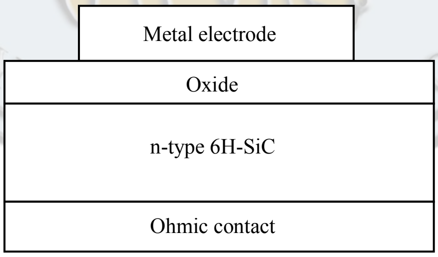

Fig. 4. SiC MOS capacitor hydrogen sensor structure.

The sensor consists of a catalytic metal plate. Pt, Pd or Ni, with a thickness of about 100 nm and a diameter between 50÷1000 μm, are often used. The hydrogen compounds best react with Pd.

Different oxides have different sensitivities to gases. A lot of investigations have been made regarding the oxide layer composition. Thus, using an oxide layer which is sensitive to gas improves the sensitivity of the MOS sensor. In this case, the gas reacts with both metal electrode and oxide layer. Moreover, a gas sensitive oxide layer can improve the selectivity of the sensor, by varying the oxide composition. Thus, a wider range of gases can be detected. The oxide usually used in this type of sensor is SiO_2 which can have a thickness between 30÷50 nm. Other oxides that have been used to detect hydrogen and hydrocarbon species were: TiO_2, WO_3, SnO_2, or Ga_2O_3.

For hydrogen detection, MOS capacitors on silicon carbide are preferred (Fig. 4). This material has several advantages over silicon: band gap of 3.02 eV, breakdown electric field of 3 MV/cm and thermal conductivity of 3÷5 W/cm·K, in the case of 6H politype [12]. These properties make it suitable for gas sensing applications in high temperature and chemically reactive environments.

3.3. Sensing Mechanism

The response of a MOS capacitor gas sensor is caused by the change of the metal work function due to a dipole layer formed by the hydrogen atoms at the metal-insulator interface. The effect of the oxide layer on sensing method is considered negligible. The response of the sensor is influenced by the gas species that interact with the sensor, the type of the metal, the operating temperature and the pressure of the environment.

The sensing mechanism will be considered in two cases: at low temperatures and at high temperatures [13].

1) Detection Mechanism at Low Temperatures

When a MOS capacitor is exposed to hydrogen, the gas molecules dissociate in contact with the metal electrode at temperatures as low as 150 °C. This is considered a low temperature for SiC MOS capacitors. Some of the hydrogen atoms remain at the surface of the metal, and others diffuse into the metal until they reach the metal-oxide interface. There is equilibrium between the number of hydrogen molecules adsorbed at the metal surface and the number adsorbed at the metal-oxide interface. The hydrogen atoms from the metal-oxide interface are polarized and create a bipolar layer. This bipolar layer decreases the metal work function which reduces the flat band voltage of the MOS capacitor. The change of the flat band voltage determines a shift of the *C-V* characteristic of the capacitor. The chemical reactions that take place in the sensing mechanism of a MOS capacitor at low temperatures are illustrated in Fig. 5. Firstly, the dissociation of hydrogen molecules at the surface of the catalytic metal takes place [14]:

$$\mathrm{H_2} \leftrightarrow 2\mathrm{H} \tag{1}$$

These atoms diffuse into the metal and reach the metal-oxide interface.

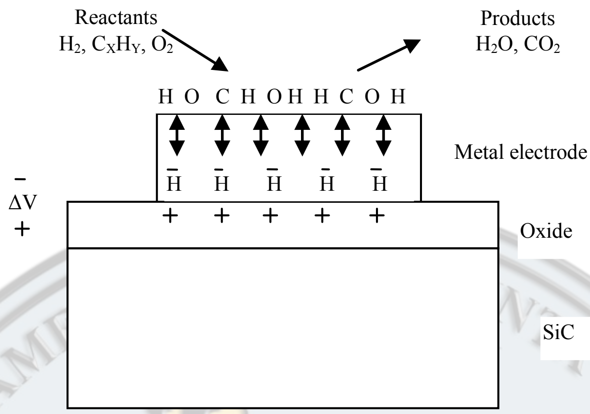

Fig. 5. Sensing mechanism for MOS capacitor hydrogen sensor.

The kinetic equations for the transport of hydrogen in the metal electrode at equilibrium state are [15]:

$$\frac{n_i}{N_i - n_i} = k_s \frac{n_s}{N_s - n_s} \frac{n_s}{N_s - n_s} = \left[\frac{c_1}{d_1} P(H_2)\right]^{1/2} \quad (2)$$

where N_s and N_i are the number of adsorption sites at the metal surface and metal-oxide interface respectively, n_s and n_i are the number of hydrogen atoms adsorbed at the metal surface and metal-oxide interface respectively, k_s and K are constants that depend on the difference between the adsorption energy at the metal surface and the adsorption energy at the interface, c_1 and d_1 are constants of forward and backward reaction rate at the metal surface (1), and $P(H_2)$ is the hydrogen partial pressure. From (2) results:

$$\frac{n_i}{N_i - n_i} = k_s \left[\frac{c_1}{d_1} P(H_2)\right]^{1/2} = K[P(H_2)]^{1/2} \quad (3)$$

The coverage of hydrogen at the metal surface (θ_s) and at the interface (θ_i) is introduced:

$$\theta_s = \frac{n_s}{N_s} \theta_i = \frac{n_i}{N_i} \quad (4)$$

Therefore, equation (3) becomes:

$$\frac{\theta_i}{1 - \theta_i} = k_s \frac{\theta_s}{1 - \theta_s} = K[P(H_2)]^{1/2} \quad (5)$$

The coverage of hydrogen at the metal-oxide interface can be expressed as a function of the hydrogen partial pressure:

$$\theta_i = \frac{K[P(H_2)]^{1/2}}{1 + K[P(H_2)]^{1/2}} \tag{6}$$

The output signal of the MOS capacitor hydrogen sensor is voltage shift (ΔV) induced in the *C-V* characteristic. This swing is proportional to the coverage of hydrogen at the interface:

$$\Delta V = \Delta V_{max}\theta_i \tag{7}$$

Where ΔV_{max} is the maximum shift of the *C-V* characteristic when the absorption sites at the interface are fully saturated ($\theta_i = 1$). The voltage change in *C-V* characteristic can be expressed also as a function of the hydrogen partial pressure:

$$\Delta V = \Delta V_{max}\frac{K[P(H_2)]^{1/2}}{1 + K[P(H_2)]^{1/2}} \tag{8}$$

The voltage shift of the *C-V* characteristic of the MOS capacitor gas sensor with *n*-type semiconductor introduced in an inert environment that contains hydrogen is illustrated in Fig. 6.

If the MOS capacitor hydrogen sensor is introduced in an atmosphere that contains oxygen, the oxygen molecules will also dissociate at the metal surface. The absorbed oxygen can react with the absorbed hydrogen and form water, which decreases the number of hydrogen atoms that reach the metal-oxide interface. The reactions that take place in the presence of oxygen are the following [13]:

$$\mathrm{H_2} \leftrightarrow 2\mathrm{H} \tag{9}$$

$$\mathrm{O_2} + 2\mathrm{H} \rightarrow 2(\mathrm{OH}) \tag{10}$$

$$\mathrm{OH} + \mathrm{H} \rightarrow \mathrm{H_2O} \tag{11}$$

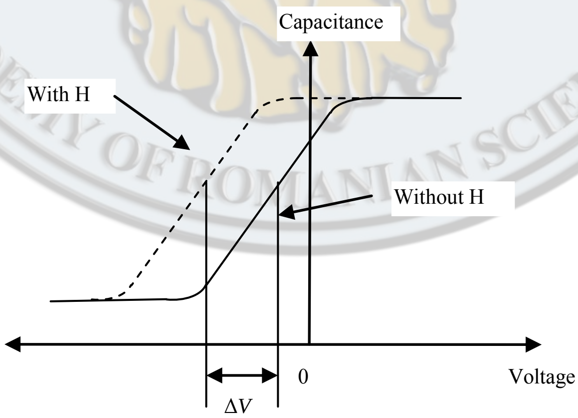

Fig. 6. *C-V* characteristic shift of a MOS capacitor with *n*-type semiconductor introduced in an inert environment that contains hydrogen at low temperature.

Thus, the voltage shift of the *C-V* characteristic is smaller. The coverage of the hydrogen at the interface becomes in this case [13]:

$$\frac{\theta_i}{1-\theta_i} = k_s\left[\frac{c_1 P(H_2)}{2c_2 P(O_2)}\right]^{1/2} \tag{12}$$

Where c_1 and c_2 are constants of the rate of the reactions (9) and (10) and $P(O_2)$ is the oxygen partial pressure.

From eqs. (7) and (12), the voltage shift of the *C-V* characteristic of a MOS capacitor sensor is:

$$\Delta V = \Delta V_{max}\frac{k_s\left[\frac{c_1 P(H_2)}{2c_2 P(O_2)}\right]^{1/2}}{1+k_s\left[\frac{c_1 P(H_2)}{2c_2 P(O_2)}\right]^{1/2}} \tag{13}$$

Thus, ΔV resulting in (13) is lower than the voltage shift obtained in the absence of oxygen molecules (see eq. (8)).

SiC MOS capacitor can also detect hydrogen in an environment which contains both hydrocarbons and oxygen. In this case, the hydrogen is dissociated from hydrocarbons. Two chemical reactions occur: between hydrogen and oxygen to form water and between carbon and oxygen to form carbon dioxide [13].

2) Detection Mechanism at High Temperatures

SiC MOS capacitor can also operate as a hydrogen sensor at high temperatures, over **700 K** [16, 18]. In this case, a passivation of oxide-semiconductor interface charges takes place (Fig. 7). As illustrated in Fig. 7a, hydrogen diffuses through the metal and forms a dipole layer at the metal-oxide interface. This dipole layer reduces the work function of the metal plate, causing a shift of the sensor *C-V* characteristic towards negative voltage axis (on *n*-SiC). The hydrogen also diffuses through the oxide layer and reaches the oxide-semiconductor interface. Here, it passivizes the interface state charges, as well as a shorter transition from accumulation to inversion on sensor *C-V* characteristic, as shown in Fig. 8 [16].

The presence of hydrogen atoms only determines the shift of the *C-V* curve with ΔV voltage. A higher slope can be observed, too (Fig. 8). Then the sensor is introduced in an oxygen environment (Fig. 7b). Oxygen dissociates in contact with metal electrode, too. As mentioned above, hydrogen reacts with these oxygen atoms and form water. Thus, a lower number of hydrogen atoms reach the metal-oxide and the oxide-semiconductor interfaces. The reduction of the hydrogen atoms causes an increase of the metal work function and a shift of the *C-V* characteristic towards the higher voltages. As well, less interface charges will be passivized by hydrogen atoms. These interface states decrease the slope of the *C-V* characteristic because the charge from the interface states reduces the voltage dependence of the depletion region width.

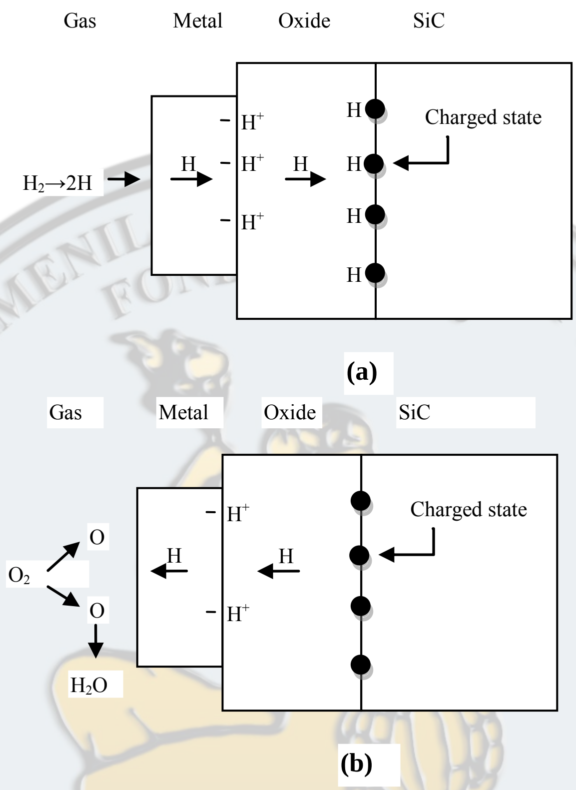

Fig. 7. Charge distribution in:
(a) hydrogen, (b) hydrogen and oxygen exposed MOS capacitor gas sensor.

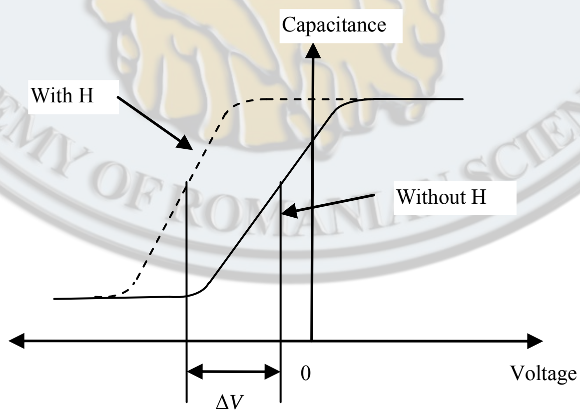

Fig. 8. *C-V* characteristic of *n*-type SiC MOS sensor
introduced in hydrogen environment at high temperature.

These differences between the *C-V* curves of the SiC MOS capacitor sensor placed in hydrogen only and in hydrogen and oxygen environments are shown in Fig. 9 [13].

The effect of hydrogen and oxygen on the shape of *C-V* characteristic is reversible. After the sensor is extracted from the hydrogen and oxygen environments, the *C-V* curve returns to the initial shape [16].

Note that the main advantage of the MOS capacitor hydrogen sensor on silicon carbide is that it can operate at high temperatures. The passivation and activation of the interface charged states take place at these elevated temperatures only [13].

The metal electrode causes the dissociation of the hydrogen molecules. The composition of the electrode is a compromise between performance and durability. In order to perform very well in the hydrogen dissociation process, the metal electrode must be thin and have a high area. So as to be durable, the metal electrode must be thick and stable.

Different materials can be used to form the metal electrode: Pd, Pt, Ni, Ir, Au, Ag. Pt has a higher catalytic activity than Pd, but hydrogen has a higher solubility in Pd. Hydrogen diffusion through Pd is very fast, less than 150 µs for a 200 nm Pd electrode at room temperature [13].

The dielectric layer has a very important role in the detection mechanism of MOS capacitor gas sensors [17]. Depending on the type of gas that needs to be detected, different oxides are employed. The most common composition of the dielectric layer in a silicon carbide MOS sensor is SiO_2 because it can be easily grown on SiC.

Other oxides have been used in SiC MOS capacitor gas sensors. One example is $BaSnO_3$ which showed a pronounced response to oxygen at temperatures above 400 °C [19]. ZrO_2 [19] and TiO_2 [20] also showed responses to oxygen containing gas species. It was discovered that ZnO is highly sensitive to concentrations of propane below 100 ppm [21]. Tungsten trioxide (WO_3) was found to be sensitive to hydrogen and NO_x [22].

3.4. Experimental SiC MOS Sensor

One example of SiC MOS sensor that was developed and characterized consists of Pt, SiO_2 on *n*-type 6H-SiC. The base of the sensor is 1 cm^2 and the oxide thickness is 43 mm. The platinum electrode has a thickness of 100 nm and a diameter between 50 µm and 1000 µm. The nominal doping of the silicon carbide layer is 1.6×10^{16} N/cm^{-3}.

Before operation, a SiC MOS sensor has to be activated. The activation consists of the introduction of the sensor in a controlled atmosphere at a temperature above

600 °C. Oxidizing and reducing gases are introduced successively in this controlled environment for several hours. Therefore, a stable and fast response of the sensor is achieved.

After activation, the sensor can operate in the desired environment. In order to determine the existence of hydrogen and hydrocarbons, the metal electrode of the MOS sensor must be in direct contact with the environment. A sensor drive circuit is used to keep the sensor capacitance to a constant value. The sensor voltage, before and after its placement in the gas atmosphere, is measured. The difference between the two measured voltages (ΔV) represents the sensor output.

The sensor was introduced in a controlled chamber. The gas composition in the chamber could be detected to the ppm level. Two types of gases were introduced to be found: nitrogen with 1.0% oxygen and nitrogen with 10.0% hydrogen. The gas flow rate was 400 mℓ/min.

A linear DC bias sweep of 0.1 V/s was applied on the capacitor structure. The capacitance of the structure was measured at 1 MHz in an ambient temperature of **800 K**. A C/C_{OX}–V characteristic was obtained (Fig. 9). In this plot C represents the measured capacitance and C_{OX} represents the capacitance of the oxide layer [8].

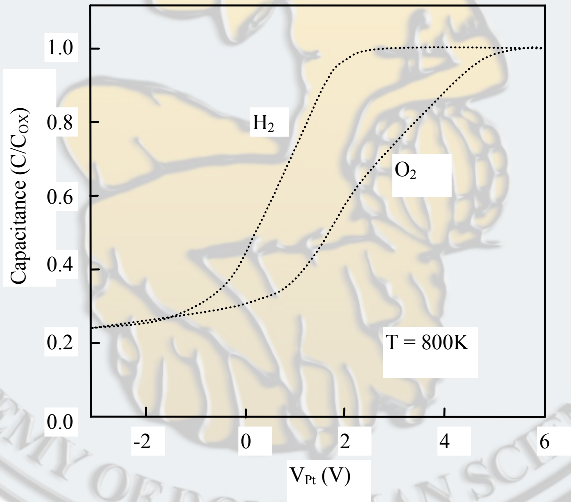

Fig. 9. *C-V* characteristic of a SiC MOS capacitor sensor at **800 K** [8].

Then the sensor is placed in a hydrogen environment, the *C-V* characteristic has a high slope in the depletion region. This is due to the fact that hydrogen atoms passivize the interface trapped charges at the oxide-semiconductor interface. If the sensor is located in a hydrogen and oxygen atmosphere, the slope of the *C-V* curve in the depletion region decreases. This is caused by a higher oxide-semiconductor interface charges. The voltage shift is also decreased because a portion of the hydrogen atoms reacts with the oxygen atoms and form water.

From *C-V* curve associated to oxygen results that the influence of the interface charge is significant at the higher values of the capacitance, where the depletion layer capacitance has a reduced contribution in the total capacitance. In this region of the *C-V* characteristic, the magnitude of the output signal is larger, but the response time is slow and the stability is affected by the large interface charge density.

The effect of the interface charge becomes negligible for the capacitance close to minimum value (C_{INV}, inversion layer capacitance value). Thus, the difference between the response in hydrogen and in hydrogen and oxygen environments respectively is insignificant. The small contribution of interface charge determines a faster and more stable response of the sensor over repeated measurement cycles. In order to find a compromise between the reliability and the speed of the response, the sensor is kept at a fixed capacitance value in the lower half of the *C-V* characteristic [8].

3.5. Improvement Methods

A lot of research is done in finding ways to increase the sensitivity of the MOS capacitor hydrogen sensors. Certain treatments applied to the sensor structure can improve the sensitivity. The sensitivity (S) is given by [24]:

$$S(\%) = \frac{\Delta C}{C} \times 100 \tag{14}$$

Where C is the capacitance in clean air and ΔC is the change in capacitance at a certain gas concentration. It was experimented that by annealing the SiO_2 layer of a MOS capacitor gas sensor with microwave and RF oxygen plasma, the sensitivity of the sensor is improved. Several sensors were annealed at different RF and microwave oxygen plasma powers. The sensitivity of the sensor increases with the plasma power. A maximum sensitivity of 74.4% was obtained by treating the sensor with a microwave and RF oxygen plasma of 200 W for 5 minutes. For a plasma over 200 W, the sensitivity of the sensor decreases with the annealing time.

4. Conclusions

SiC MOS capacitor is mainly used as a hydrogen and hydrocarbon sensor. Hydrogen detection has attracted great attention in recent decades because of the larger usage of such gas. Hydrogen is used as a clean energy source in fuel cells and is a part of hydrocarbon compounds which cause damage to the environment.

Different types of hydrogen sensors were developed, each of them having advantages and disadvantages. Catalytic combustion sensors have limited sensitivity, poor selectivity and consume a lot of power. Piezoelectric sensors have poor sensitivity and are influenced by temperature and gas flow rate. Most of the hydrogen sensors cannot be integrated in sensor arrays.

The SiC MOS capacitor hydrogen sensor has high sensitivity (down to ppm level) and selectivity. It also has fast response, at **800 K** the diffusion time of hydrogen through 100 nm of Pt electrode is less than 5 μs and through 50 nm of SiO_2 is less than 500 μs. The SiC MOS capacitor sensor has low power consumption (can be supplied with batteries), small size and can be integrated in sensor arrays. It is very simple and easy to fabricate. The recovery time is very short.

However, SiC MOS capacitor needs to be activated by placing it in a controlled environment which alternately contains hydrogen and oxygen. Moreover, the errors caused by the interface states at elevated temperatures must also be taken into account.

A thorough understanding of the competing phenomena responsible for the electronic and chemical properties of SiC MOS structures will enable the design of more stable and reliable high temperature sensors based on silicon carbide.

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