Pulse Biasing Scheme for the Fast Recovery of FET-Type Gas Sensors for Reducing Gases

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***Abstract*—The promotive effect of a pre-bias condition on the recovery speed of a Field-Effect-Transistor (FET)-type gas sensor, which has a horizontal control-gate (CG) and floating-gate (FG), is investigated in this study. To verify the pre-bias effect in the recovery phase after the detection of H_2S gas, a type of reducing gas, a 200-nm-thick layer of SnO_x is deposited on top of the interdigitated CG and FG as a sensing material. A pulse measurement method is proposed to improve the recovery speed of the sensor for H_2S gas sensing by applying a negative pre-bias condition to the CG before the read operation of the sensor. This method greatly accelerates the recovery and reduces the recovery time by 74% with a pre-bias of −3 V at 180 °C. The mechanism is explained in terms of energy band theory. The pre-biasing method used with our gas sensor is beneficial for the continuous monitoring and for the rapid detection of various gases.**

***Index Terms*—pre-bias effect, recovery speed, reducing gas, work-function, FET platform, gas sensor**

I. Introduction

FET-type gas sensors with porous metals [1] or air gaps [2]–[4] have attracted much attention. These devices have been widely investigated for the detection of hazardous waste gases produced by industrial or domestic fuel combustion owing to their low power consumption and good reproducibility [4], [5]. Target gas molecules adsorb on the surface of porous metals or sensing materials and change the work-function of the gate, so that the V_{th} of the FET will be tuned. However, the FET sensor with a porous metal [1] usually cannot detect large gas molecules, because large gas molecules cannot pass through the pores of the gate metal, causing the work-function to remain constant. According to literature [2]–[4], with a suspended gate forming an air gap between the gate and the insulator above the channel, gases are allowed access easily to the sensing material attached to the bottom of the gate. However, the air gap dimension should be optimized to obtain reasonable work-function sensitivity and the suspended gate complicates the fabrication processes as well. To evade these issues, an FET-type gas sensor platform with horizontal FG and CG components was proposed in our previous work [6]. Due to the horizontally interdigitated pattern of the FG and CG, a variety of sensing materials can be formed in the sensor during the final process step to protect the FET from contamination. Good compatibility with conventional CMOS process technology expands the application of gas sensing systems consisting of a sensor array and circuits on the same substrate for in-situ gas detection and identification. Moreover, the capacitive coupling between the two gates, which affects the sensitivity of the device [3], [6], is enhanced due to the interdigitated pattern of the FG and CG.

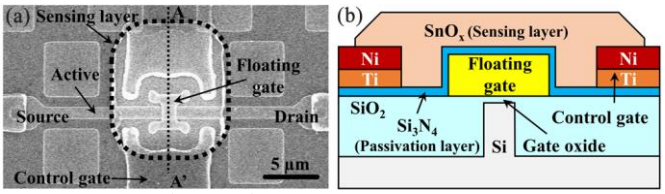

Fig. 1. Structure of the platform gas sensor. (a) Plane SEM image. (b) 2-D Schematic cross-sectional view cut along line A-A' in (a).

Sensors for the detection of H_2S have been recently developed in a series of studies [7]–[14] using different kinds of materials as H_2S is one of the most critical exhaust gases. Among them, metal oxides, especially tin oxide, have been widely adopted [14]–[19]. H_2S molecules react with the oxygen ions on the surfaces of SnO_x particles to change the electrical properties of the SnO_x. After the sensing operation, oxygen molecules in the ambient environment will be chemisorbed again during the recovery process. However, because oxygen molecules react with SnO_x slowly, the recovery time is relatively long, which restrains the application of the sensors in continuous monitoring and rapid detections of various gases. Thus, it is necessary to improve the recovery speed.

In this work, we deposit SnO_x thin film on top of our FET-type gas sensor platform to detect H_2S and investigate the sensing characteristics. Specifically, a pulse measurement method is proposed to reduce the recovery time of the sensor after the H_2S gas detection step. We explain the principle behind the promotive effect of the negative gate pre-bias on the recovery speed by means of energy band theory.

II. Fabrication and Device Structure

Fig. 1(a) and (b) show an SEM image and a 2-D cross-sectional image cut along A-A', respectively. The FET-type sensor has the FG and CG formed horizontally and the SnO_x sensing material covering both the gates and the space

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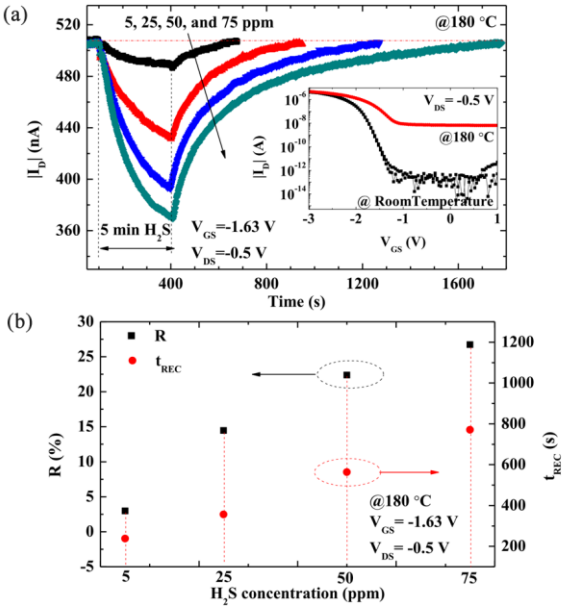

Fig. 2. (a) Transient $|I_D|$ characteristics for detecting H_2S gas at 180 ℃ measured by DC measurements. The inset shows double sweep DC I-V curves at room temperature and 180 ℃. (b) Changes in R and t_{REC} with the concentration of H_2S. The response time t_{RES} and recovery time t_{REC} are defined as the rise time of $|I_D|$ to 90% of its maximum value and the fall time to the 10% of the difference between the maximum and reference current levels.

between them. Both the gate length and width of the FET are 1.2 μm. The fabrication process of the sensor can be found in our previous paper [6]. In the present work, a sensor platform based on a *p*MOSFET is adopted because *p*MOSFETs have less flicker noise than *n*MOSFETs [20]. The thickness of the thermally formed SiO_2 gate oxide is 10 nm. A 200-nm-thick in-situ phosphorous-doped Poly-Si layer is deposited as the FG, followed by the formation of 50-nm-thick Si_3N_4 as a passivation layer. Note that the Si_3N_4 layer also electrically isolates the sensing material and the FG while protecting the gate oxide the channel from various gases and moisture. A 200-nm-thick CG consisting of 20-nm-thick Ti and 180 nm of Ni is formed on both sides of the FG horizontally and interdigitally to improve the coupling ratio. Finally, a 200-nm-thick SnO_x sensing layer is formed to cover the FG and CG by a sputtering process. Sample target gases are prepared by mixing 500 ppm of H_2S diluted in N_2 with dry synthetic air (20 vol. % of O_2 and 80 vol. % of N_2). The sensing characteristics are tested at 180 ℃ by switching the ambience between the dry air and the target gas (H_2S). Electrical measurements were carried out using an Agilent B1500A device with a pulse measurement module on a Waveform Generator/Fast Measurement Unit (WGFMU).

III. Results and Discussion

Double-sweep I-V curves at room temperature and 180 ℃ are measured (Fig. 2(a) inset) and the sensing properties of the FET sensor for H_2S gas are characterized by DC measurements as shown in Fig. 2. In this case, amounts of 5 to 75 ppm of H_2S gas are supplied from 100 s to 400 s, after which dry air is supplied. The responses of the sensor are shown in Fig. 2(a). In the transient measurements, constant biases of −1.63 V and −0.5 V are applied to the CG and drain electrodes, respectively.

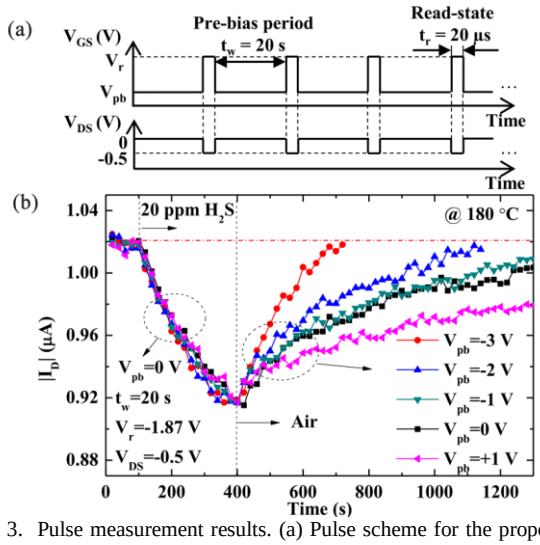

Fig. 3. Pulse measurement results. (a) Pulse scheme for the proposed pulse measurement. (b) Transient $|I_D|$ behavior as a parameter of V_{pb}.

The response (R) of the gas sensor to H_2S is defined as

$$R = [(|I_{D\_R}| - |I_{D\_G}|)/|I_{D\_R}|] \times 100\% \quad (1)$$

where I_{D_R} and I_{D_G} represent the reference drain current in ambient air and the current in the target gas mixture, respectively. The response time (t_{RES}) and recovery time (t_{REC}) are defined as the rise time of $|I_D|$ to 90% of its maximum value and the fall time to 10% of the difference between the maximum and reference currents. Fig. 2(b) shows the changes in R and t_{REC} with the concentration of H_2S. A higher concentration induces a larger R but a longer t_{REC}. For 75 ppm of H_2S gas, $|I_D|$ decreases from 500 nA (I_{D_R}) to 371 nA (I_{D_G}) during the response period. The values of R, t_{RES}, and t_{REC} are 54%, 205 s and 771 s, respectively. In this case, t_{REC} is more than three times longer than t_{RES}, which makes the continuous monitoring and rapid detection of various gases difficult.

In order to reduce the recovery time of the sensor for H_2S gas, a pulse measurement method is proposed. We devise a pulse scheme in which appropriate pre-bias (V_{pb}) and read bias (V_r) levels are applied sequentially. It is important to note when V_{pb} is applied to the CG, V_{DS} is set to 0 V simultaneously to mitigate any unwanted power consumption, while during the read operation, both V_r and V_{DS} are synchronized and have finite biases. The pulse scheme used in this work is shown in Fig. 3(a). Here, the widths of the V_{pb} pulse (t_w) and the V_r pulse (t_r) are set to 20 s and 20 μs, respectively. Fig. 3(b) shows the transient $|I_D|$ behavior as a function of V_{pb} applied during recovery after the detection of 20 ppm H_2S. Taking the results of V_{pb}=0 V as the reference, a V_{pb} value of 1 V induces a longer t_{REC}. However, as V_{pb} decreases from 0 V to −3 V, the t_{REC} gradually decreases. The t_{REC} values with V_{pb}=−3 V and 0 V are 247 s and 960 s, respectively. Additionally, the t_{REC} is reduced by nearly 74% when adopting a negative V_{pb}. According to previous findings by authors [21], a positive V_{pb} can reduce the t_{REC} of the SnO_x sensor for oxidizing gases (NO_2), which has the opposite effect for reducing gases (H_2S in this paper). Moreover, we suggested that the redox characteristics of a certain target gas can be identified using pulse schemes having

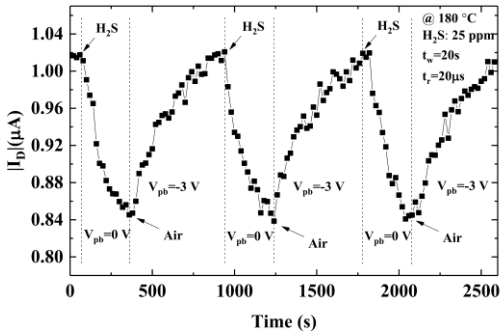

Fig. 4. Repeated measurements with alternate exposures to 25 ppm of H_2S gas and air. V_{pb} in the response and recovery phases are 0 V and −3 V, respectively.

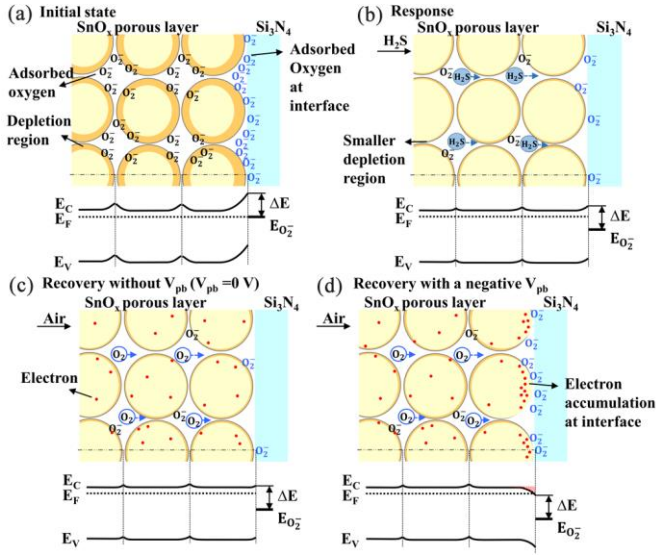

Fig. 5. Adsorption/reduction of oxygen molecules/ions and energy band diagrams at the interface between SnO_x and Si_3N_4 when the ambience and V_{pb} are changed. (a) Initial state before the detection of the target gas. Oxygen molecules reacting with SnO_x take up electrons from SnO_x and become ionized. The energy band bending of SnO_x at the interface is determined by the acceptor E_{O2}- of O_2^-. (b) Response to H_2S. The energy band bending decreases because electrons transfer back to SnO_x due to the reducing reaction between H_2S and the oxygen ions. (c) Natural recovery with V_{pb} =0 V. (d) Recovery with a negative V_{pb}. The energy band diagrams of (c) and (d) are both at the state just before recovery. Downward band bending can be found in (d) compared with that in (c) because more electrons accumulate at the interface, which accelerates the recovery.

different polarities of the V_{pb} [21]. This statement is verified here by the pulse measurement results of H_2S in this paper. Fig. 4 shows the drain current change when the gas sensor is alternately exposed to 25 ppm of H_2S gas and air three times in a row. The V_{pb} in the response phase is 0 V. To make the recovery speed fast, a V_{pb} of −3 V is applied to the CG in the recovery phase. The t_w and the t_r are 20 s and 20 μs, respectively, which are the same as those in Fig. 3. Three consecutive cycles show almost similar response and recovery characteristics.

Fig. 5 shows the adsorption/reduction of oxygen molecules/ions and corresponding energy band diagrams at the interface between SnO_x and Si_3N_4 when the ambience and V_{pb} are changed. Before the detection of H_2S gas, oxygen ions (O_2^-) already exist on the surfaces of the SnO_x particles [22] due to the ionization of oxygen from the extraction of electrons from SnO_x, as shown in Fig. 5(a). According to the literature [23], [24], adsorbed O_2 molecules can be considered as a local accepter (E_{O2}-). The difference between the valance band E_C of SnO_x and E_{O2}- is denoted by ΔE. When the sensor is exposed to H_2S gas, H_2S molecules penetrate the porous sensing layer, finally reaching the interface between the sensing and passivation layers and reacting with O_2^- as explained by (2) [16], [17]. During this period, the electrons will revert to SnO_x. Both the depletion region and the upward band bending of SnO_x gradually decrease until the sensing is saturated, as shown in Fig. 5 (b). As the ambience changes back to air, the sensor starts to recover naturally at 180 ℃ with the ionization of re-physisorbed oxygen molecules from the air as explained by (3). Fig. 5(c) presents the natural adsorption of oxygen molecules during the recovery period and the corresponding energy band diagram just before the recovery process begins. However, for the pulse measurement shown in Fig. 5(d), applying a negative V_{pb} to the CG will cause the energy band of SnO_x to bend downward at the interface because SnO_x is an *n*-type semiconductor material [23], [25] and acts as a part of the CG due to the ohmic contact with CG metal. Here, the energy band diagram is still in the state just before the recovery. In this way, more electrons accumulate at the interface comparing to that under the read bias such that more oxygen molecules will be ionized per unit of time. Therefore, faster recovery can be observed with a negative V_{pb}.

$$2H_2S + 3O_2^- \xrightarrow{\text{adsorption}} 2SO_2 + 2H_2O + 3e^- \quad (2)$$

$$O_2 + e^- \xrightarrow{\text{desorption}} O_2^- \quad (3)$$

IV. Conclusion

In summary, we investigated the promotive effect of a pre-bias (V_{pb}) condition on the recovery speed of a *p*FET-type gas sensor with a FG and CG horizontally after detecting H_2S gas. The slow chemical reaction between oxygen molecules and SnO_x during the recovery period induces a long recovery time, which greatly restrains the use of these types of sensors to continuous monitoring and rapid gas detection applications. Therefore, a pulsed pre-bias scheme was proposed to reduce the recovery time. By applying a negative V_{pb} before the read operation of the sensor, the energy bands of SnO_x are bent downward as this material is an n-type semiconductor. Therefore, more electrons accumulated at the interface between SnO_x and passivation layer, which significantly promoted the ionization of oxygen molecules per unit of time to hasten the recovery speed. This work also verified that the redox characteristics of a certain target gas can be identified using pulse schemes having different polarities of V_{pb}.

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