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A novel Pd/oxide/GaAs metal_insulator_semiconductor field-effect transistor (MISFET) hydrogen sensor

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Abstract

A novel and high-performance Pd/oxide/GaAs hydrogen sensor based on a metal-insulator-semiconductor field-effect transistor (MISFET) is fabricated and studied. In the presence of the interfacial oxide, high sensitivity and significant increase in output drain current are observed. In the presence of hydrogen, a $2 \times 200 \ \mu m^2$ gate dimension device shows good dc characteristics including high turn-on voltage, an obvious variation of drain current and a short response time. In addition, under the applied voltage of $-4 \ V$ and 537 ppm hydrogen in air, a very high sensitivity of 9473 is obtained. This performance shows that the device studied has a good potential for high-speed and high-sensitivity hydrogen sensor and MISFET integrated circuit applications.

1. Introduction

The leakage detection of specific gases into the environment, such as carbon monoxide, ammonia and hydrogen, is very important in industrial fabrication processes and medical installations, etc. Recently, some reliable, low-cost, high-sensitivity and small-dimension gas sensors have been produced successfully and reported in [1–3]. Different types of the familiar Pd/SiO₂/Si MOS devices, such as capacitors and Schottky diodes, were reported by Eriksson and Ekedahl [4]. Experimental results show their remarkable high-sensitivity characteristics in digital applications. However, most of these devices have some drawbacks, including (i) the necessity of operation at elevated temperatures and (ii) the very small amplitude of the output electric signals. In order to overcome these problems, gas sensors based on the field-effect transistor (FET) structure have been

investigated and reported [3]. Generally, metal–oxide– semiconductor field-effect transistors (MOSFETs) based on silicon technologies have been well developed to achieve high detection sensitivity [5]. On the other hand, solid-state hydrogen sensors based on III–V compound semiconductor devices are expected to have the advantages of shorter response times and better temperature stability. Yet these type of sensors are relatively rarely found.

In this paper, a novel hydrogen-sensing GaAs FET with a Pd membrane on the interfacial oxide layer is proposed. The presence of the interfacial oxide layer exhibits advantages including the (1) larger turn-on voltage as compared with conventional metal–semiconductor field-effect transistors (MESFETs) [6] and (2) high sensitivity [7]. The detailed description of the device structure and fabrication are presented in the next section. In section 3, experimential results and discussions are presented. Finally, a conclusion is drawn.



Figure 1. The schematic cross section (a) and corresponding energy band diagram (b) of the device studied.

2. Experiments

The Pd/oxide/GaAs metal-insulator-semiconductor fieldeffect transistor (MISFET) structure to be studied was grown on a (100) oriented semi-insulated (SI) GaAs substrate by a metal organic chemical vapour deposition (MOCVD) system. The epitaxial structure consisted of a 0.5 μ m thick GaAs undoped buffer layer and a 0.3 μ m thick n-GaAs (n = 1.5×10^{17} cm⁻³) active layer. After epitaxial growth, drain and source contacts were deposited on the n-GaAs active layer by AuGe/Ni and alloyed at 450 °C for 25 s. Then, the mesa etching process was used to etch the wafer into the substrate in a 5NH₄OH : 3H₂O₂ : 100H₂O solution at 4 °C. The native oxide was removed by a solution of 1HF: 1H₂O. Then, the samples were placed in a thermal oven with O2 flow at 360 °C for 25 min to form the oxide layer. The thickness of the oxide layer is about 40–50 Å. Finally, the evaporated Schottky gate contact was produced by Pd metal. The gate dimension is $2 \times 200 \ \mu m^2$. The dc characteristics were measured by using an HP4156A semiconductor parameter analyser.

3. Results and discussion

The schematic cross section of the device studied is shown in figure 1(a). For hydrogen adsorption and desorption measurement, the devices were placed in a closed stainlesssteel reaction chamber connected to a gas flow tube with a regulating valve. Different concentrations of hydrogen gas in air (48, 97, 202 and 537 ppm) were employed in this study. The chamber was maintained at a pressure of one atmosphere and the continuous and stable gas flowing at a 500 sccm flow rate was introduced into the chamber. Figure 1(*b*) illustrates the corresponding energy band diagram of the fabricated device. The hydrogen-sensing mechanism can be expressed by the reaction kinetics as follows [8]:

$$\mathbf{H}_{2g} \stackrel{c_1}{\underset{d_1}{\leftarrow}} 2\mathbf{H}_a \stackrel{c_2}{\underset{d_2}{\leftarrow}} 2\mathbf{H}_b \stackrel{c_3}{\underset{d_3}{\leftarrow}} 2\mathbf{H}_i \tag{1}$$

where c_1, c_2, c_3 and d_1, d_2 and d_3 are adsorption and desorption rate constants. H_{2g} , H_a , H_b and H_i are gaseous hydrogen, hydrogen atoms adsorbed species, hydrogen atoms adsorbed on the Pd bulk and hydrogen atoms at the Pd-oxide interface, respectively. Due to the catalytic performance of Pd metal, the adsorbed hydrogen molecules on the Pd metal surface are dissociated into hydrogen atoms. The hydrogen atoms diffuse and pass through the Pd metal and form a dipole layer at the metal and semiconductor interface. This dipole layer can decrease the depletion width and further lower the metalsemiconductor Schottky barrier height. The polarization of the dipole layer either neutralizes the donor level, decreasing the pinning effect, or causes the reversible reduction of barrier height in the H₂ environment. The dipole layer is generated by hydrogen atoms at the Pd/oxide interface as indicated in figure 1(b). The dipole layer between metal and semiconductor corresponds to a voltage drop and therefore changes the characteristics of the MISFET studied. The presence of the interfacial oxide causes the (1) decrease in the depletion region, (2) reduction of the barrier height, (3) increase of the interface charges and (4) avoidance of the Fermi level pinning effect [9, 10].

Figure 2 shows the corresponding gate–drain current– voltage (I-V) characteristics of the Pd/oxide/GaAs MISFET studied measured under different hydrogen concentrations at room temperature. The corresponding turn-on voltages, defined at the gate current of 0.1 mA mm⁻¹, are 0.73, 0.676, 0.67, 0.658 and 0.62 V, respectively, as shown by the



Figure 2. The gate-to-drain I-V characteristics of the fabricated device under different hydrogen concentrations.

upper inset in figure 2. The relatively higher gate turn-on voltages of the MISFET studied are mainly attributed to the insulated oxide layer. In addition, the reverse leakage currents increase with increasing the hydrogen concentration. This is attributed to the tunnelling mechanism [11] and reduced Schottky barrier height. The corresponding reverse breakdown voltages, defined at the gate current of 0.1 mA mm⁻¹, are -12.6, -6.2, -6, -5.65 and -5.35 V, respectively. The relationship between the gate current (I_g) and gate-to-drain voltage (V_{GD}) from -3 to -5 V is shown in the lower inset of figure 2. The detection sensitivity S [12] can be defined as

$$S = \frac{I_{\rm H_2} - I_{\rm air}}{I_{\rm air}} \tag{2}$$

where I_{H_2} and I_{air} are currents measured under a hydrogencontaining ambient atmosphere and air, respectively. It is worth noting that the sensitivity of the reverse current from air (the reference) to 537 ppm hydrogen/air environment approaches the high value of 9743 at $V_{GD} = -4$ V. This high sensitivity is mainly attributed to the presence of the interfacial oxide layer in the device studied, as mentioned earlier [10].

The common source output I-V characteristics at room temperature are illustrated in figure 3(a). As shown in this figure, the drain saturation current distinctly increases with increasing hydrogen concentration. All I-V curves show good pinch-off and cut-off behaviour. Figure 3(b) shows the corresponding output I-V characteristics at 100 °C. As shown in figure 3(b), an obvious current collapse phenomenon at 100 °C and 537 ppm hydrogen concentration is found. This phenomenon could be partially attributed to the selfheating effect.

The extrinsic transconductance g_m and output drain saturation current density I_{DS} as a function of gate-to-source voltage V_{GS} of the device studied is shown in figure 4. The maximum values of g_m are 84.4, 83, 81.1, 79.8 and 77.7 mS mm⁻¹ in air and at a hydrogen concentration of 48, 97, 202 and 537 ppm, respectively. The corresponding drain saturation currents at $V_{GS} = 0$ V are 193, 198.1, 198.9, 201.4 and 202.5 mA mm⁻¹, respectively. Clearly, the transconductance g_m decreases with increasing hydrogen concentration. On the other hand, the drain saturation current increases with increasing hydrogen concentration and exhibits a linear behaviour with V_{GS} .

Figure 5 shows the variation of extrinsic transconductance Δg_m and threshold voltage ΔV_{th} as a function of hydrogen concentration for the device studied. Δg_m and ΔV_{th} are differential values of extrinsic transconductance and threshold voltage measured under a hydrogen-containing ambient atmosphere and in air, respectively. Clearly, the magnitudes of Δg_m and ΔV_{th} increase with increasing hydrogen concentration. With increasing hydrogen concentration, the MISFET studied shows a rapid decrease in drain current at higher hydrogen concentrations, the leakage current is dominated by the generation/recombination mechanism. Yet, at higher hydrogen concentrations, the diffusion dominates the leakage current [13].

Without the introduction of hydrogen gas, the output I-V characteristics at room temperature are almost similar to those at higher temperatures without the added hydrogen. The behaviour is in good agreement with the results reported by Gobert and Salmer [14]. In other words, the temperature effect for the MISFET studied is not obvious. The drain saturation current of a MISFET can be expressed as [15]

$$I_{\rm Dsat} = \frac{1}{2} \mu_n C_{ox} \frac{W}{L} (V_{GS} - V_{th})^2$$
(3)

where μ_n , C_{ox} , W, L and V_{th} denote the electron mobility, oxide capacitance, gate width, gate length and threshold voltage, respectively. As shown in the experimental results, the increase of the drain current at room temperature is primarily attributed to the change in the gate built-in potential. This change results from the adsorption of hydrogen atoms on the surface state, which form dipoles at the gate metal/oxide interface as shown in figure 1(b). From equation (3), as the threshold voltage (V_{th}) is reduced, the drain saturation current is increased. Generally, the threshold voltage is directly proportional to the built-in potential of the MISFET. The decrease in the built-in potential is caused by the formation of dipoles. This behaviour further confirms that the presence of dipoles at the Pd/oxide interface will decrease the depletion region and strongly influence the electrical signals. Hence, with increasing hydrogen concentration, the drain saturation current I_{Dsat} is increased. At 100 °C and 537 ppm hydrogen concentration, as shown in figure 3(b), the current collapse phenomenon is caused by the tunnelling effect, carrier multiplication induced by the lowering of the barrier height [16] and a decrease in electron mobility with increasing the temperature [17].

Figure 6 shows the hydrogen transient response for the introduction and removal of 202 and 537 ppm hydrogen/air gases at the reverse bias of $V_{GD} = -4$ V and 100 °C. The reverse current shifts rapidly to the steady-state value upon hydrogen adsorption (point a) and hydrogen desorption (point b). Generally, the response time constants, including



Figure 3. Output *I*–*V* characteristics of the fabricated device under different hydrogen concentrations at (*a*) room temperature and (*b*) 100 °C. The gate voltage is supplied by -0.5 V/step and the maximum gate voltage is $V_{GS} = 0$ V.



Figure 4. The extrinsic transconductance g_m and the drain saturation current I_{DS} as a function of the gate-to-source voltage V_{GS} for the device studied.

(This figure is in colour only in the electronic version)

the adsorption and desorption time constants τ_a and τ_b , are defined as the times reaching e^{-1} of the final steady-state current values. The τ_a values under 202 and 537 ppm hydrogen/air gases are 2.8 and 2.6 s, respectively. In addition, the corresponding τ_b values are 3.2 and 2.9 s, respectively. The response times (τ_a and τ_b) decrease when the hydrogen concentration is increased. The shorter reaction time can be explained by the larger interface cover sites and a larger collision-induced reaction rate.



Hydrogen Concentration (ppm)

Figure 5. The change of transconductance (Δg_m) and threshold voltage (ΔV_{th}) as a function of hydrogen concentration at room temperature.

4. Conclusion

In summary, a high-performance hydrogen sensor based on a Pd/oxide/GaAs MISFET structure is fabricated successfully. The oxide layer is employed to improve the turn-on voltage and hydrogen detecton sensitivity by eliminating the Fermi-level pinning effect. At room temperature, the sensitivity of the reverse current can approach approximately four orders of magnitude for the 537 ppm hydrogen/air condition. In addition, the device studied exhibits obvious modulation of the drain current



Figure 6. Transient response curves with the introduction and removal of 202 and 537 ppm hydrogen/air gases at 100 °C.

(of the order of mA). The short response time constants of 2.8 and 2.6 s are observed for the 202 and 537 ppm hydrogen/air conditions, respectively, at 100 °C. Therefore, the device studied shows great promise for high-speed and high-sensitivity hydrogen sensor and MISFET integrated circuit applications.

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