High Electron Mobility Transistors Based Hydrogen Sensor with Gas-Sensing Chip

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***Abstract*—In this work, a novel hydrogen detector consisted hydrogen sensor and gas sensing circuitry was proposed. The interesting hydrogen–sensing properties of catalytic Pd/AlGaAs metal-semiconductor (MS) and metal-oxide-semiconductor pseudomorphic high electron mobility transistors (pHEMT) based hydrogen sensor are studied and compared. The remarkable saturation current variations show that both hydrogen sensors are suitable to operate at room temperature. The detecting sensing of the MOS-type hydrogen sensor is superior to that of the MS-type. In addition, the integrated output circuitry was connected to the studied hydrogen sensors. In contrast to the conventional voltage divider read-out technique, a novel differential read-out circuit is proposed. The integrated output circuit applied a current mirror as constant current to drive the sensor. The applied signals were selected by the switch and decoder. Finally, the signal was output by a differential read-out circuit.**

***Keywords*- hydrogen detector, gas-sensing chip, saturation current variation, pHEMT**

1. Introduction

Due to the progressive requirements of energy source and environmental protection, the detection of hydrogen has become an important issue [1]. The applications of hydrogen in modern technology include industrial fabrication process, medical treatment and hydrogen fueled vehicles etc. Recently, many solid-state hydrogen sensors, based on different substrates, have been studied and reported [2-5]. As compared with the Si-based hydrogen sensors, the compound semiconductor based devices show the benefit includes higher detection sensitivity, shorter response time, and higher operation temperature [4, 5]. In the practical field of gas sensors, most of the read-out circuits were realized by an application-specific integrated circuit (ASIC). However, the volume of gas detector is large. The monolithic hydrogen sensor with in-chip circuitry can drawback this disadvantage. However, the post fabrication of gas sensor is difficult. Hence, in this work, a novel separate type hydrogen detector was proposed. The hydrogen detector consist hydrogen sensors and gas sensing circuitry. The hydrogen sensors were fabricated based on compound semiconductor. The gas sensing circuitry consist several integrated circuits realizing by CMOS technology. The hydrogen array includes thre hydrogen sensors include a Au/AlGaAs metal-semiconductor, Pd/AlGaAs metal-semiconductor (MS) and metal-oxide-semiconductor (MOS) pseudomorphic high electron mobility transistors (pHEMT) based hydrogen sensor are studied and compared. Based on the variations of the catalytic metal work function, the DC characteristics of experimental results are studied and compared. Also, the integrated sensing circuit is connected to the studied hydrogen sensor. In contrast to the conventional voltage divider read-out technique, a novel differential read-out circuit is proposed. The integrated output circuit applied a current mirror as constant current to drive the sensor. The applied signals were selected by the switch and decoder. Finally, the signal was output by a differential read-out circuit. The output voltage transfer curves can be obtained and demonstrated.

2. Experimental

The gate dimension of the studied device is $1.4 \times 100 \mu m^2$. The typical eqitaxial layer structure is shown in figure 1. Conventional photolithography, vacuum evaporation, lift-off, and wet etch techniques were used to form the electrode pattern. The ohmic contacts were deposited on the n^+-GaAs cap layer by AuGe/Ni metals. Then AuGe/Ni metals were alloyed at 450℃ for 10 minutes in order to penetrate the n^+-GaAs cap layer and reach the n-AlGaAs active layer. A mesa etching process was used to etch the wafer into the substrate by the solution of NH_4OH : H_2O_2 : H_2O = 5 : 3 : 100 at 4℃ for GaAs and $Al_{0.3}Ga_{0.7}As$. Then, the drain-source Ohmic contacts were formed on the n^+-GaAs cap layer by evaporating Au/Ge/Ni metals and subsequently alloyed at 380°C for 20 seconds. The native oxide on the wafer was removed by the solution of HF: H_2O = 1 : 1. Then, the samples were divided into two groups. The wafers in the first group, i.e., MOS type devices, were placed in a thermal oven with O_2 flow at 360℃ for 35 minutes to form a thin and fresh oxide layer on the surface. The other samples, however, i.e., MS-type devices, were not processed with oxidation step. In this paper, Device A is Pd/AlGaAs MS hydrogen sensor, Device B is Pd/AlGaAs MOS hydrogen sensor. Device C is Au/AlGaAs MS hydrogen sensor. However, the device did not show and hydrogen sensing response. Finally, the evaporated Schottky contact was produced by the evaporation of Pd metal on the surface of the thin oxide layer (MOS-type) and n-AlGaAs (MS-type), respectively. Different hydrogen concentrations in air of 15, 200 and 1000 ppm H_2/air were used in this study. The experimental current-voltage (*I-V*) characteristics of hydrogen sensors were measured by a Keithley model 4200 semiconductor characterization system.

In order to measure the differential hydrogen sensing functions for the studied devices, a multiplexing circuit is required to select 1-of-3 hydrogen sensor. Fig. 2 shows the integrated circuitry which is connected with the studied devices. The integrated circuit includes four parts. Part A allows input several hydrogen sensors which are fabricated as sensor array. Device A and Device B were set here. Part B is the switch circuit. Part C is a decoder. Part D is the differential readout circuit. The hydrogen sensing signals of device A or device B were selected by the multiplexing circuits. Finally, the signals were output by the differential readout circuit.

3. Experimental Results and Discussion

Figure 3 shows the schematic of differential readout circuit.

The transmission gates can improved the noise margin as compared with the traditional switch by using NMOS. Figure 4 shows the schematic of transmission gate. Table 1 is the related features of the gas sensing chip. The integrated circuitry is fabricated by TSMC0.35 2P4M technology.

The voltage difference across the output can be express as

$$V_o^+ - V_o^- = I_{ref} \times R \qquad (1)$$

Were V_o^+ and V_o^- are the positive and negative differential outputs. R is the hydrogen sensor's resistance. I_{ref} is the bias current created by the cascade current mirrors. In the differential readout circuit, the aspect ration of MOSFET7 and MOSFET8 are equal. Hence, we can obtained that

$$V_{dd} = V_o^+ + V_o^- \qquad (2)$$

Combing Eq.(1) and Eq. (2), we obtain:

$$V_o^+ = \frac{V_{dd}}{2} + \frac{I_{ref} \times R}{2} \qquad (3)$$

$$V_o^- = \frac{V_{dd}}{2} - \frac{I_{ref} \times R}{2} \qquad (4)$$

From the result of Eq.(3) and Eq.(4), we can obtain that the output voltage is independent form the transistor parameters. This is an important issue for readout circuit's application.

The typical common-source output current-voltage (*I*-*V*) characteristics of the studied device under air and 200ppm H2/air hydrogen gas at 30℃ are shown in Fig.5. Both of studied devices exhibit remarkable hydrogen detecting capability at room temperature. The current variation of MOS structure is larger than that of MS type. This is attributed to the reduction of the leakage current resulting from the improved interface properties under the presence of interfacial oxide layer. The studied devices provide a better choice for practical integrated circuit (IC). Due to the large variation of drain current by introduced hydrogen gas, the hydrogen response can be obtained directly.

Fig. 5 shows the transient response curves of MS type and MOS type hydrogen upon the introduction and removal of 200 and 1000ppm H2/air gases of the studied device at room temperature. The voltage of VGS=-0.3V and VDS=1.2V are applied. The response curves shift rapidly from transient state to steady upon hydrogen adsorption (point A) and hydrogen desorption (point B). The positive temperature dependence of adsorption reaction rate can be attributed to the increased hydrogen dissociation adsorption and diffusion coefficients.

Figure 6 shows the measured hydrogen sensing response of 200 ppm H_2/air extract from Pd/AlGaAs MOS device. The signal of hydrogen sensing current is marked as dashed line. The signal measured form the circuitry is marked as solid line. Clearly, the measured signals from gas sensing circuitry have twice time as compared with the signal of hydrogen sensor.

4. Conclusion

This paper reports the design, fabrication and experimental measure of hydrogen sensor together with its integrated gas sensing circuitry. The high performance compound semiconductor based hydrogen sensors exhibit remarkable variation of hydrogen sensing current, even operated at room temperature. A novel differential read-out circuit achieves good results in terms of common mode noise and power supply rejection.

ACKNOWLEDGMENT

The authors are grateful to Professor W. C. Liu for helpful discussion and Chip Implementation Center (CIC) for supporting integrated circuit fabrication. Part of this work was supported by the National Science Council of the Republic of China under contract no NSC 96-2221-E-324-053

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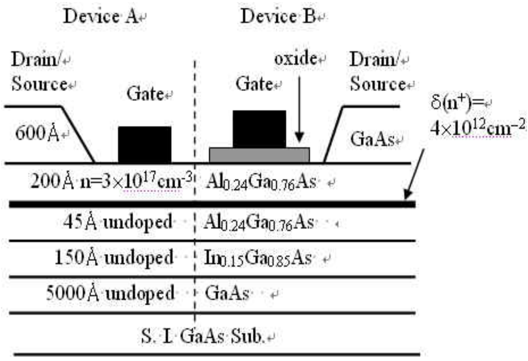

Fig.1 Schematic cross-sections of the studied device A and B.

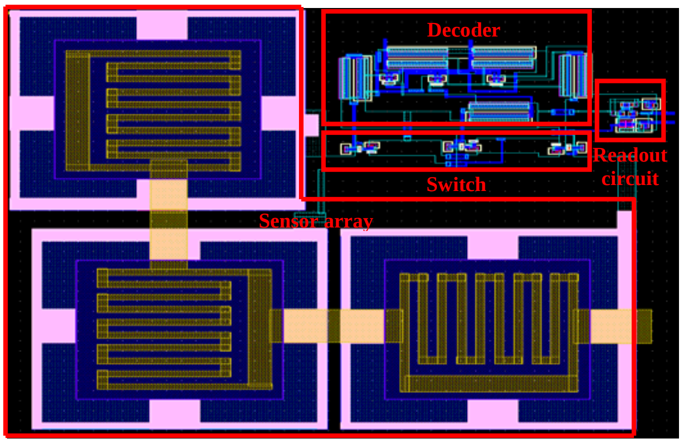

Fig.2 Microphotograph of the integrated hydrogen sensor array and its pre-processing circuits.

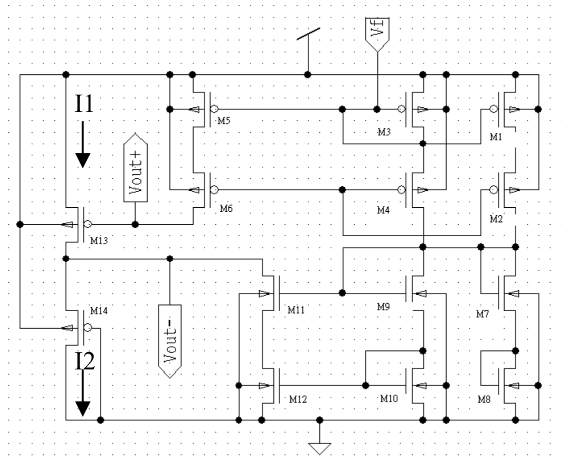

Fig.3 Schematic of the differential readout circuit.

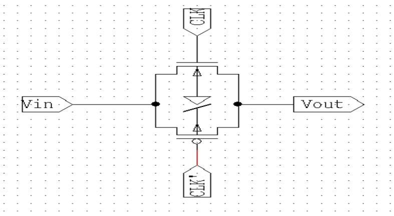

Fig.4 transmission gate is used in the switch circuit.

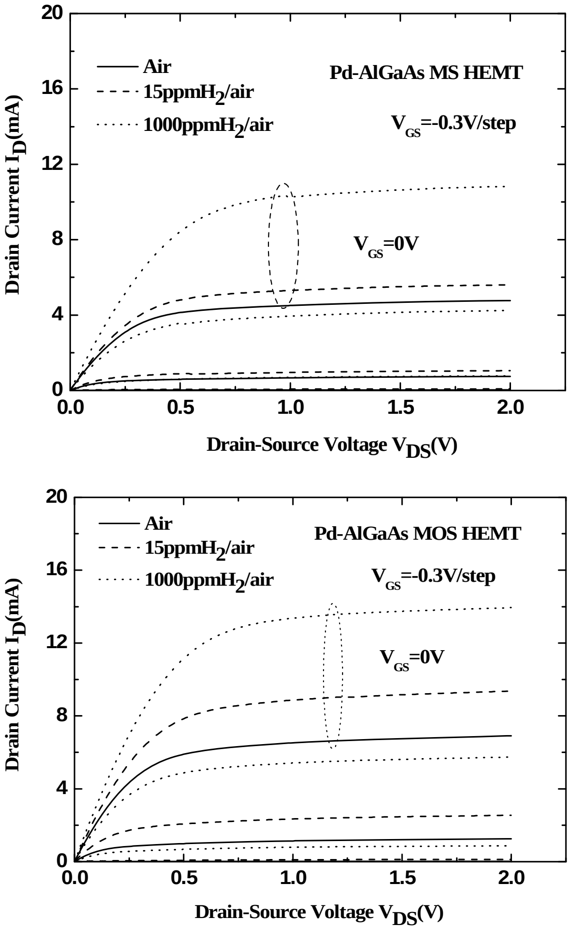

Fig. 4 Common-Source output I-V Characteristics of (a) device and (b) device in differential hydrogen concentration at room temperature.

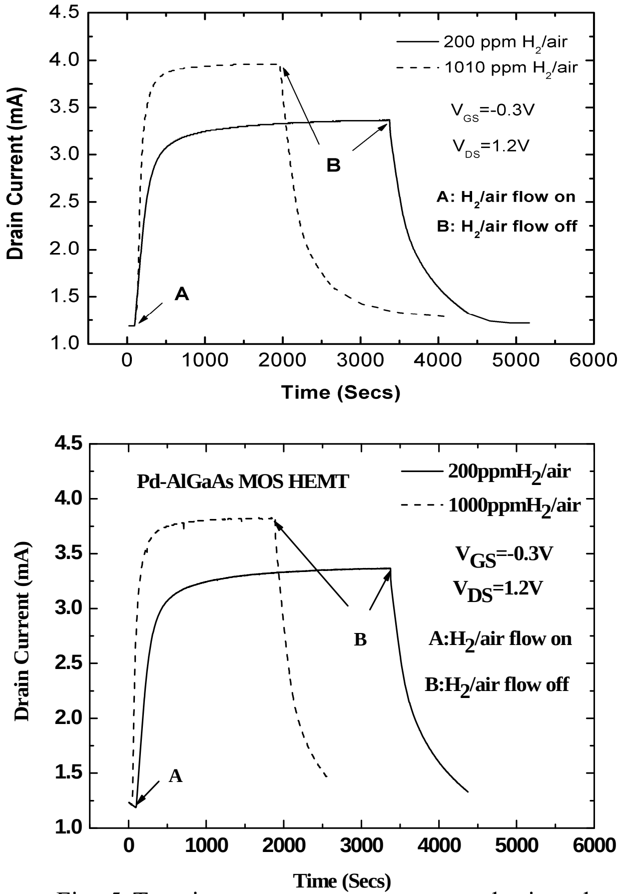

Fig. 5 Transient response curves upon the introduction and removal of 200 and 1010ppm H_2/air gases of (a) the studied device A and (b) the studied device B at room temperature.

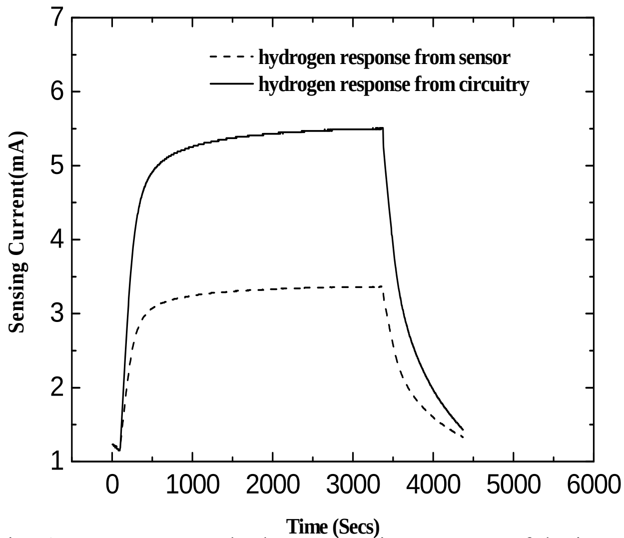

Fig. 6 Measure output hydrogen sensing currents of device B from the hydrogen sensor (dash line) and hydrogen sensing circuitry (solid line) under 200 ppm H_2/air.

Table 1 the related features of the gas sensing chip

Fabrication technology	TSMC 0.35um 2P4M
Supply voltage	3.3V
Input voltage	0V~1.4V
Input frequency	40Hz
Output voltage	V_{O+}:2.48V，V_{O-}:2.48V
Output frequency	40Hz
Power consumption	820.7670 u W
Chip Area	0.987 x 1.325 mm^2