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AlGaN/GaN HEMT Based Hydrogen Sensors With Gate Absorption Layers Formed by High Temperature Oxidation

I. Rýger[a] *, G. Vanko[a], P. Kunzo[a],T. Lalinský[a], M. Vallo[a], A. Plecenik[b], L. Satrapinský[b], T. Plecenik[b]

[a]*Institute of Electrical Engineering, Slovak Academy of Sciences, Bratislava, Slovakia*
[b]*Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava, Slovakia*

Abstract

We present a new approach in design of high temperature stable AlGaN/GaN HEMT gate absorption layers for hydrogen sensing at elevated temperature. To suppress undesirable chemical interaction of Pt on the gate interface, a thin conductive IrO_2 oxide layer (t ~ 10 nm) is formed by high temperature oxidation (T= 800 °C for 1min in O_2 ambience) before Pt catalytic metal deposition. The comparative study of the hydrogen detection on AlGaN/GaN HEMT device with the Pt and Pt-IrO_2 based gate absorption layers is shown. The sensitivity of the Pt gate Schottky diode is significantly enhanced with the insertion of IrO_2 gate interfacial layer. The proposed Pt-IrO_2 gate based diode exhibits a maximum sensing response value of 70 %/ppm at 100 °C under a 0.1 % H_2/N_2 gas. As comparing with the conventional Pt diode it is increased by more than 12 times. Additionally, the operating temperature for the maximum sensing response is decreased from 150 °C to 100 °C with the insertion of IrO_2 interfacial layer. Moreover, the Schottky gate barrier height lowering at is found to be 254 meV and 100 meV for the IrO_2 and Pt gate based diodes, respectively.

Keywords: Hydrogen; gas sensor; gate oxide; Schottky diode; HEMT; AlGaN/GaN;

1. Introduction

Hydrogen gas is widely-used in chemical industry. It is used in catalytic Fischer-Tropsch process as well-known synthesis gas (H2+CO) [1]. Moreover, the hydrogen gas is considered to be environmentally clean alternative to gasoline. Solid oxide fuel cells operate at elevated temperature (500-1000 °C typically) [2]. Hydrogen gas is also used in catalytic hydrogenation of backed vegetable fat [3]. However,

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* Corresponding author. Tel.: +421 2-5922-2739; fax: +421 2-5477-5816.
E-mail address: ivan.ryger@savba.sk.

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high-concentration hydrogen gas in air (≥4.65%) is inflammable and explosive. With the increasing necessity of electric energy, the safety has become an important issue. Therefore, small sensors capable of high temperature operation with a fast response are indispensable for hydrogen applications. Gallium nitride (GaN) based wide band gap compound semiconductor material systems have recently appeared to be very attractive for design of hydrogen sensors [4-8]. They are very promising candidates mainly for high temperature gas sensing applications in harsh environments. Currently, various AlGaN/GaN based hydrogen sensing devices such as Schottky diodes [1], metal-semiconductor-metal (MSM) diodes [5], and metal-oxide-semiconductor (MOS) diodes [5] have been introduced to demonstrate high sensitive and fast detection of hydrogen. Surprisingly little effort has been directed toward the study of sensor devices which involve the HEMT operation principle directly [6, 7].

To demonstrate high sensitive and fast detection ability of the HEMT based sensor device at high operation temperatures, new high temperature stable Schottky gate absorption layers are needed. A conventional thin Pt catalytic metal in role of gate absorption layer could operate up to 800 °C [8] provided the formation of intermetallic PtGa phase on the gate interface with the temperature is suppressed. To avoid undesirable chemical interaction of Pt on the gate interface very thin interfacial conductive IrO_2 oxide layer (t~10 nm) is formed by high temperature oxidation (T=800 °C for 1 min) before Pt catalytic metal deposition.

1.1. Experiment

An undoped GaN(3 nm)/AlGaN(17 nm)/GaN(1.7 μm) heterostructure was grown by MOCVD technique on a 470 μm thick SiC substrate layer. The Al mole fraction in the AlGaN barrier layer is 0.295. The circular HEMTs were fabricated using Nb/Ti/Al/Ni/Au ohmic contacts, which were annealed at 850 °C for 35 s. Iridium electron beam evaporation and lift-off were carried out subsequently to form a thin (10 nm) gate contact. Afterwards, the thermal oxidation of Ir gate contact was performed in O_2 ambience using RTA at 800 °C for 1 min. The gate layer is followed by the thin Pt (15 nm) sensing layer. Ti/Au (20/150 nm) metallic layers are patterned on the top of the alloyed ohmic contacts to improve bonding facility. The total Schottky contact area for both Pt and Pt/IrO_2 samples was 1.32×10^{-3} cm^2. The total uncovered absorption area was 1.04×10^{-3} cm^2.

The sensor was tested in chamber of total volume of 125 cm^3. The sample was heated by ceramic thermal heater with PID temperature stabilization. Precise hydrogen concentration was held constant during measurement by mass-flow controllers. The volumetric flow rate was set to 125 cm^3/min. The measurement consists of following steps:

- Temperature set-up.
- Nitrogen applied for 10minutes.
- Nitrogen+Hydrogen mixture applied for 10minutes.
- Nitrogen applied for 10minutes.

These steps were repeated at different temperatures.

1.2. Results and Discussion

Fig. 1 shows the impact of interfacial IrO_2 gate layer on surface roughness of top Pt catalytic layer. It can be seen that the insertion of IrO_2 (Fig. 1b) eliminates the surface roughness of Pt (Fig. 1a) probably due to the formation of PtGa intermetallic phase at high temperature operation (high temperature annealing). It seems that IrO_2 interlayer could serve as an effective diffusion barrier against Ga atoms from the AlGaN barrier layer. In addition it improves surface-to-volume ratio of absorption layer.

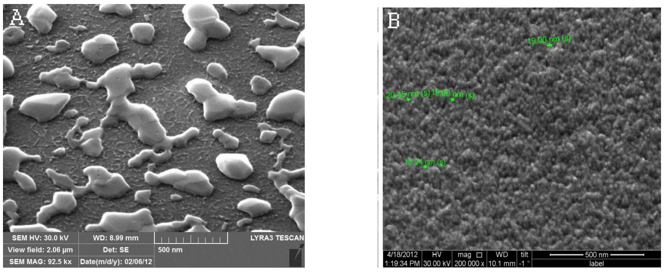

Fig. 1. Morphology of Pt electrode (a) and Pt/IrO$_2$ electrode (b) after annealing at 800°C.

Fig. 2. (a) shows the sensor response to applied 0.1 % H$_2$ in N$_2$ carrier gas. The sensitivity of Pt/AlGaN/GaN and Pt/IrO$_2$(10 nm)/AlGaN/GaN is 4.5 %/ppm and 70 %/ppm, respectively. This value corresponds to the Schottky barrier height decrease from 1.015 eV (in N$_2$ gas) to 0.915 eV (in N$_2$+H$_2$ mixture) with Pt/AlGaN/GaN sensor. On the other hand, the Pt/IrO$_2$/AlGaN/GaN sensor exhibits larger Schottky barrier height lowering. The barrier decreases from 1.305 eV in N$_2$ gas to 1.051 eV in N$_2$+H$_2$ mixture. These values were obtained from the thermoemission model.

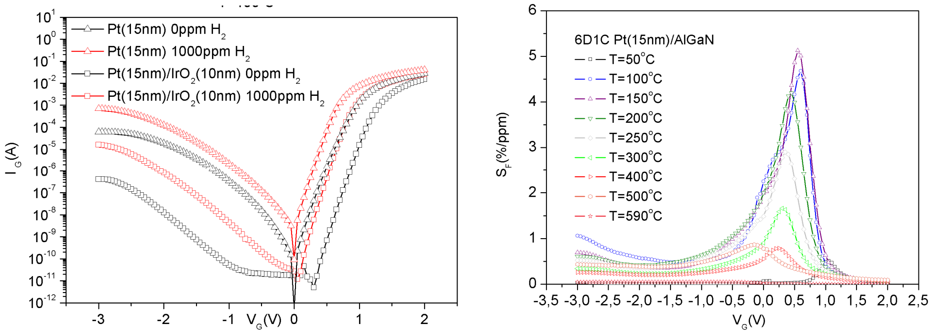

Fig. 2. Schottky I(V) characteristics of the diode gas sensor, T=100 °C (a) and sensitivity as a function of diode bias voltage (b).

The Richardson constant was taken from [9]. We also found out, that the diode sensitivity is dependent on bias voltage (Fig. 2 (b)). From the temperature dependence of diode sensitivity, the maximum sensitivity is obtained at 100 °C (Fig. 3. (a)).

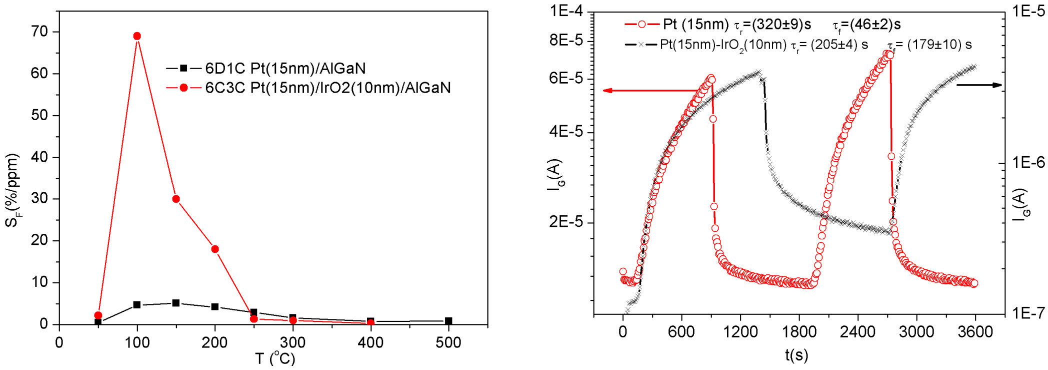

Fig. 3. Comparison of the sensitivity of Pt and Pt/IrO$_2$ Schottky gas sensor (a) and transient characteristics of sensors (b).

We performed the time-domain measurements of both sensors. The gate bias was held constant at 0.7 V. Ambient temperature was set to 50 °C and the hydrogen concentration step was 0-1000 ppm. From Fig. 3 (b) we can see that the Pt/IrO_2/AlGaN sensor reacts faster to applied concentration step (τ_R =205 s) when comparing to standard Pt/AlGaN sensor (τ_R=320 s). On the other hand, the regeneration of the Pt/AlGaN sensor is faster (τ_F=46 s) if compared to Pt/IrO_2/AlGaN sensor (τ_F=179 s).

1.3. Conclusions

The comparative study of the hydrogen detection on AlGaN/GaN HEMT device with the Pt and Pt-IrO_2 gate based absorption layers is presented in this work. To improve sensitivity and ability for high temperature sensing a new design of HEMT gate absorption layer is introduced. It uses a thin (~10 nm) interfacial IrO_2 gate layer formed by high temperature oxidation (T=800 ℃ for 1 min) before the deposition of Pt catalytic gate metal. High temperature forming of IrO_2 suppresses the undesirable formation of intermetallic PtGa phase on the gate interface at high temperature device operation.

The benefit of the proposed Pt-IrO_2 gate based absorption layer is demonstrated by the enhanced hydrogen sensing performance as compared with the conventional Pt gate based absorption layer.

The Pt-IrO_2 diode exhibits a maximum sensitivity value of 70 %/ppm at 100 °C under a 0.1 % H_2/N_2 gas. As comparing with the Pt diode it is increased by more than 12 times. Additionally, the operating temperature for the maximum sensing response is decreased from 150 °C to 100 °C with the insertion of IrO_2 interfacial layer. Moreover, the Schottky gate barrier height lowering at optimal hydrogen sensing conditions is found to be 254 meV and 100 meV for the IrO_2 and Pt gate based diodes, respectively.

Acknowledgements

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