Applied Surface Science xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Applied Surface Science

journal homepage: www.elsevier.com/locate/apsusc

Full Length Article

InGaP/InGaAs field-effect transistor typed hydrogen sensor

Jung-Hui Tsai*, Syuan-Hao Liou, Pao-Sheng Lin, Yu-Chi Chen

Department of Electronic Engineering, National Kaohsiung Normal University, 116 Ho-ping 1st Road, Kaohsiung 802, Taiwan

ARTICLE INFO

Article history:
Received 29 August 2016
Received in revised form 8 February 2017
Accepted 26 March 2017
Available online xxx

Keywords:
Pd
Mixture
InGaP/InGaAs
Field-effect transistor
Hydrogen sensor
Nanoparticle

ABSTRACT

In this article, the Pd-based mixture comprising silicon dioxide (SiO_2) is applied as sensing material for the InGaP/InGaAs field-effect transistor typed hydrogen sensor. After wet selectively etching the SiO_2, the mixture is turned into Pd nanoparticles on an interlayer. Experimental results depict that hydrogen atoms trapped inside the mixture could effectively decrease the gate barrier height and increase the drain current due to the improved sensing properties when Pd nanoparticles were formed by wet etching method. The sensitivity of the gate forward current from air (the reference) to 9800 ppm hydrogen/air environment approaches the high value of 1674. Thus, the studied device shows a good potential for hydrogen sensor and integrated circuit applications.

1. Introduction

Hydrogen has been considered to be an energy carrier and is generally used in chemical industry, semiconductor fabrication, medical treatment, and hydrogen-fueled vehicles [1]. Because hydrogen isn't sensed by the human olfactory system and its wide range of ignition in air, many researchers have paid attention to develop reliable gas sensors sensitive to hydrogen. Hydrogen has been reported to alter the effective charge at the metal-semiconductor (MS) interface or metal-insulator (MI) interface, resulting in the changes in barrier height. Furthermore, III–V semiconductor hydrogen sensors based on MS Schottky diodes have been demonstrated to operate and/or to integrate with other electronic and optical components [2–4].

Pd and Pt are the two well-known catalytic metals in hydrogen sensors, and the semiconductor-based hydrogen sensors fabricated with such catalytic metals are of particular potential. With specific catalytic activity of Pd and Pt, hydrogen molecules are adsorbed and dissociated on Pd (or Pt) metal surface, followed by rapid diffusion of hydrogen atoms into the MS (or MI) interface where the dipoles are formed to modulate the barrier height [5,6]. Moreover, sensing ability of the sensors also depends on the properties of the hydrogen adsorption states at the interface. Therefore, porous-like sensing metals are used to take the advantages of an increased surface-to-volume ratio and an enhanced dissociation rate [7]. Besides, silicon dioxide (SiO_2) used as a supporting layer was generally employed to improve the interfacial properties [8].

Previously, in digital applications gas sensors based on field-effect transistor (FET) structure have been investigated and reported [9–12]. Hydrogen sensors based on III–V compound semiconductor devices are expected to have the advantage of high electron mobility. In this article, a Pd-SiO_2 mixture catalytic material is employed in fabrication of hydrogen sensors based on InGaP/InGaAs doping-channel field-effect transistor (DCFET). The mixture as-deposited is wet selectively etched to turn into Pd nanoparticles supported by an interlayer with oxygen. A larger surface-to-volume ratio together with wider pores offers hydrogen a higher dissociation rate to increase the hydrogen/air sensitivity of the FET.

2. Experimental

The studied DCFET was grown on an (100) oriented semi-insulating GaAs substrate by a low-pressure metal-organic chemical-vapor deposition system (LP-MOCVD). The epitaxial structures consisted of a 0.5 μm undoped GaAs buffer layer, a 150 ($n^+ = 3 \times 10^{18}$ cm^{-3}) $In_{0.15}Ga_{0.85}As$ doped-channel layer, a 300 undoped $In_{0.49}Ga_{0.51}P$ gate layer. Finally, a 500 ($n^+ = 1 \times 10^{19}$ cm^{-3}) GaAs cap layer was deposited on the gate layer. Trimethylindium (TMI), trimethylgallium (TEG), phosphine (PH_3), and arsine (AsH_3) were used as the In, Ga, P, and As sources, respectively. The dopants used for n and p layers were silane (SiH_4) and dimethylzine (DMZ), respectively. Drain and source ohmic contacts were performed by evaporating AuGeNi metal on the n^+-GaAs cap layer and alloyed at

* Corresponding author.
E-mail address: jhtsai@nknucc.nknu.edu.tw (J.-H. Tsai).

http://dx.doi.org/10.1016/j.apsusc.2017.03.246
0169-4332/

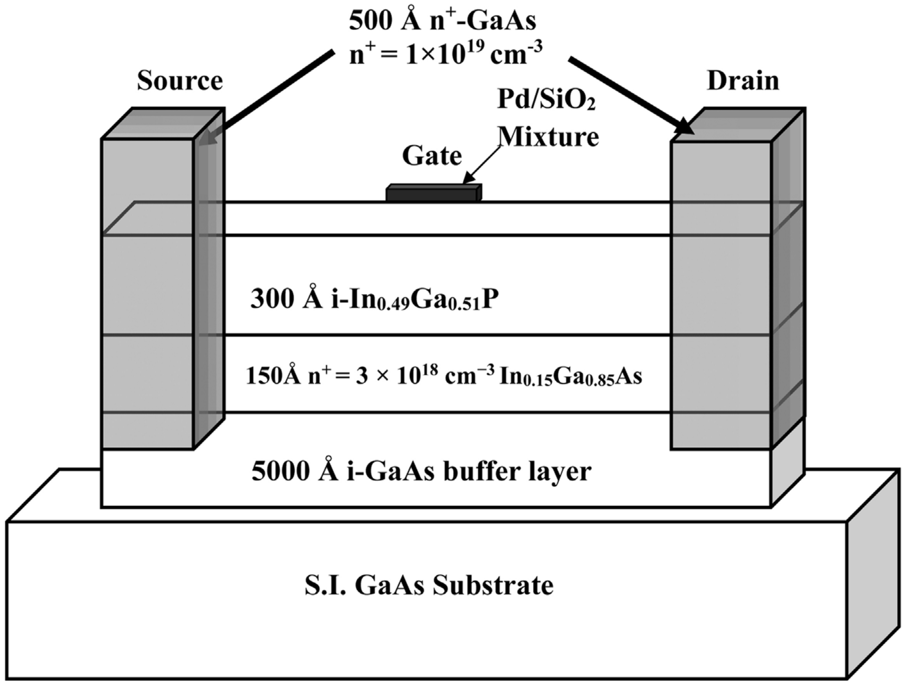

Fig. 1. Schematic cross sections of the studied device.

400 °C for 30 s. Then, a chemical solution of H_3PO_4: H_2O_2: H_2O = 1: 1: 20 was used to remove the n^+-GaAs cap layer and to form the gate recess.

After the above process, a 30 nm mixture of Pd and SiO_2 thermally deposited upon the gate layer is used as the porous-like sensing metal. The mixture was deposited at a deposition rate of 80 nm/min using a conventional thermal evaporator under a background pressure of 2×10^{-7} Torr with a deposition source of Pd: SiO_2 = 1:2 (in weight). Then, wet etched in a solution of HF: H_2O = 1: 50 to selectively remove the SiO_2 inside the mixture. Many pores and cleavage-like gaps can be found at the surface of the Pd/SiO_2 mixture. The detailed process and method are depicted in our previous report [13]. Finally, a mesa structure provided the required isolation. Fig. 1 depicts the schematic cross section of the device. The gate dimension and drain-to-source spacing were $1 \times 100\ \mu m^2$ and 3 μm, respectively. Static sensing currents reflecting various hydrogen-containing gases were performed by mounting the sensors on a test fixture with bonding wires contacting to electrodes.

3. Experimental results and discussion

Fig. 2 shows the corresponding energy band diagram of the device with and without the hydrogen sensing conditions. When the hydrogen concentration is increased, the gate barrier height of the FET sensor will be effectively decreased. This polarized layer will cause a significant barrier lowering effect as more hydrogen atoms are absorbed to form it. Most hydrogen atoms will diffuse through the mixture and arrive at the InGaP gate surface where dipoles are formed. Rough surface together with pores formed by Pd nanoparticles offers an increased surface-to-volume ratio for hydrogen molecules being dissociated. That is to say, the dipole layer between metal and semiconductor will correspond to a significant voltage drop, and therefore the characteristics of the DCFET are changed.

At room temperature, the measured gate-to-drain (G-D) current-voltage (I–V) forward characteristics of the studied Pd/SiO_2-mixture DCFET under different hydrogen concentrations are illustrated in Fig. 3. As defining the gate current at 10^{-5} A, the

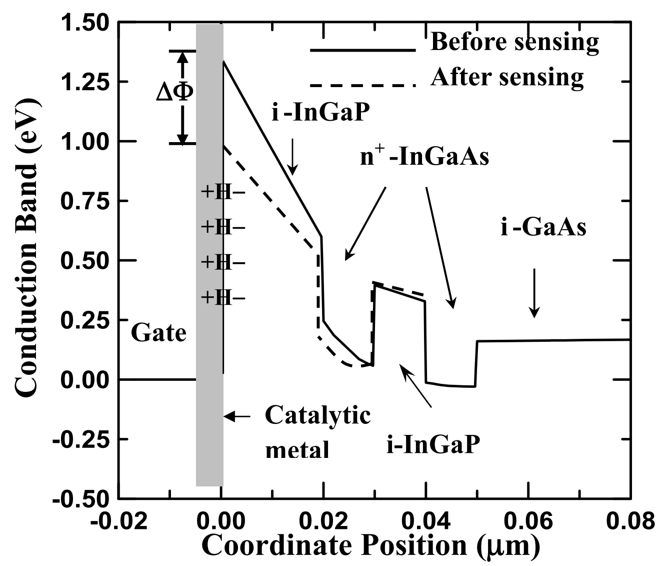

Fig. 2. Corresponding energy band diagram of the device with and without the hydrogen sensing conditions.

turn-on voltages are of 0.755, 0.66, and 0.59 V in air and at hydrogen concentrations of 980 and 9800 ppm, respectively. The large gate turn-on voltages of the studied DCFET can be attributed to the good confinement effect for electrons in channel by the employment of InGaP/InGaAs pseudomorphic heterostructure. In the relationship between the forward gate current (I_g) and G-D voltage (V_{GD}), the detection sensitivity S can be defined as [14]

$$S = \frac{I_{H_2} - I_{air}}{I_{air}} \quad (1)$$

where I_{H2} and I_{air} are currents measured under a hydrogen-containing ambient atmosphere and air, respectively. It is worthy to note that the sensitivity of the forward current from air (the reference) to 9800 ppm hydrogen/air environment approaches a high value of 1674 at V_{GD} = 0.4 V. This high sensitivity is mainly

Please cite this article in press as: J.-H. Tsai, et al., InGaP/InGaAs field-effect transistor typed hydrogen sensor, Appl. Surf. Sci. (2017), http://dx.doi.org/10.1016/j.apsusc.2017.03.246