English

Transient response of a transistor-based hydrogen sensor

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The transient phenomenon of hydrogen-sensing of a Pd-oxide-InGaP metal-oxide-semiconductor field effect transistor (MOSFET) is studied. Due to a high activation energy needed for initiating the reverse hydrogen releasing process, the responsive current signal during hydrogen detection does not always go back to the baseline. Over the high temperature region, the recovering curve can be divided into three parts: (i) the initial, (ii) the accumulation, and (iii) the revival stages. Because the recombination process of hydrogen atoms is very slow, a large amount of desorbed hydrogen atoms are appeared and accumulated on the Pd metal surface. A long desorption time is observed. However, in the presence of oxygen, a high speed desorption phenomenon is observed. The hydrogen adsorption rate is also enhanced.

With the advance of technology development, the hydrogen gas has been widely used in chemical industry, semiconductor fabrication, medical treatment, and hydrogen fuelled vehicles. In application, the hydrogen gas has the risk to induce explosion. Thus, continuous monitoring of hydrogen gas with a high-sensitive sensor becomes an important issue. Semiconductor devices such as Schottky diodes, capacitors, and field-effect transistors with different catalytic metal gates have been used as hydrogen sensors for a long time. Due to the advantages of down-sizing and cost reduction in the fabrication, these sensors are undoubtedly of great importance in the development of microelectronics based smart hydrogen-sensing systems. Generally, the hydrogen gas may effectively dissociate on a Pd metal surface with a relatively high catalytic cracking coefficient. The Pd metallization is thus a preferable choice for the hydrogen-sensing field. In this work, a Pd-oxide-InGaP metal-oxide-semiconductor (MOS)-type field-effect resistor-based hydrogen sensor is fabricated and studied. The effect of carrier gases on the hydrogen current–responses and the influence of surface chemical reactions are investigated.

The studied field-effect transistor-based hydrogen sensor was grown by a low-pressure metal organic chemical vapor deposition (LP-MOCVD) system on semi-insulated (S.I.) GaAs substrate. The epitaxial structure consisted of an undoped GaAs buffer layer, an undoped $In_{0.15}Ga_{0.85}As$ channel, an undoped $Al_{0.24}Ga_{0.76}As$ spacer, a Si planar-doped sheet, an n-$In_{0.49}Ga_{0.51}P$ Schottky contact layer, and an n$^+$- GaAs cap layer. The drain-source Ohmic contacts were formed by evaporating Au/Ge/Ni metals on the n$^+$-GaAs cap layer. The samples were immediately put into an oven with an O_2 flow to form the desired fresh oxide layer. Finally, the gate Schottky contacts with a gate length of 1.4 um were achieved by depositing the catalytic Pd metal on the InGaP layer. During the hydrogen adsorption and desorption measurement, the studied devices were placed in a stainless-steel reaction chamber with a gas flow tube and a regulating valve.

Fig. 1 illustrates the transient response for the studied device upon introduction and removal of 9970ppm of H_2 using N_2 as a carrier gas at room temperature. The highly pure nitrogen gas is introduced to set a drain current baseline of 4.74 mA. As the hydrogen gas (9970ppm of H_2 using N_2 as a carrier gas) is added into the test chamber, the detecting signal is increased rapidly. As the time goes on, a quasi-saturation phenomenon becomes gradually apparent (as shown in region a). This means that a dynamic equilibrium between the hydrogen adsorption and desorption is established. Under this condition, the maximum current variation is obtained to be 4.0mA. In region b, the hydrogen gas is shut off and simultaneously pure nitrogen gas is introduced. Clearly, the recovery phenomenon of the studied device is very slow.

Fig. 1. Transient response curve upon introduction and removal of a 9970ppm H_2/N_2 gas at room temperature under the applied voltages of $V_{GS} = -0.3V$ and $VS = -1.2$ V.

Typical dynamic changes in drain current ID as a function of time upon exposure to different hydrogen concentrations from 5 to 9970ppm of H_2/N_2 gas at room temperature are shown in Fig. 2. Obviously, even at an extremely low hydrogen concentration of 5ppm H_2/N_2, a large current variation of 2.80 mA is found at room temperature. However, long response time more than 5 h is observed. When the high hydrogen concentration is introduced, the corresponding response time is decreased. In comparison with the H_2/air environment, it is difficult to detect the low hydrogen concentration due to the formation of hydroxyls and water. Too much oxygen gas will reduce the detecting limit
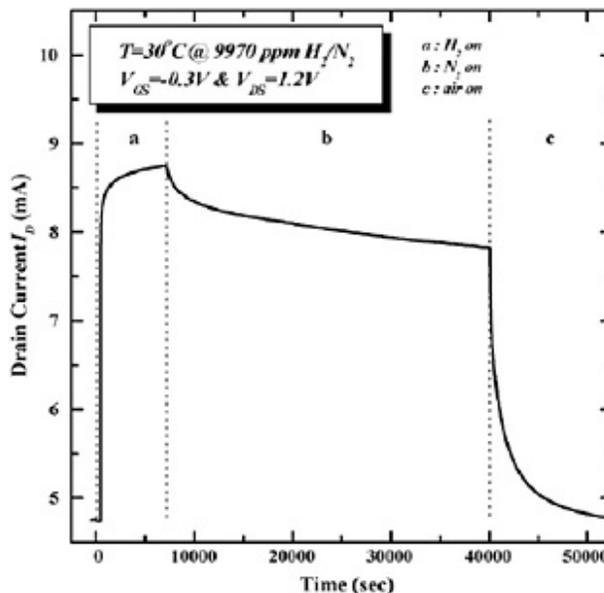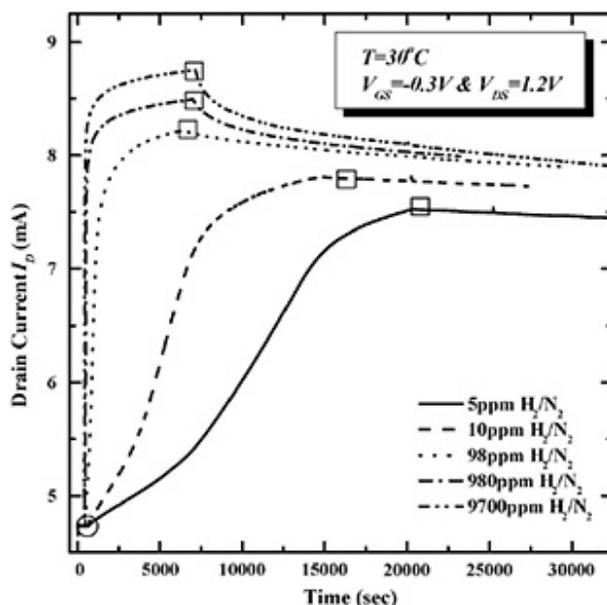

Fig. 2. Typical dynamic changes in drain current ID as a function of time upon exposure to different hydrogen concentrations from 5 to 9970ppm H_2/N_2 at room temperature.
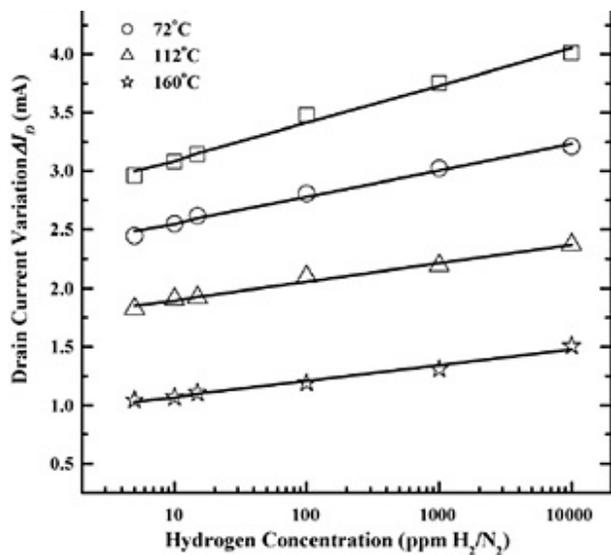
Fig. 3. The relationship between the drain current variation and hydrogen concentration in N_2 environment at temperatures from 30 to 160 exposure to a 9970ppm H_2/N_2 gas.

Fig. 4. Transient response curves with two testing gases of (i) 9970ppm H_2/N_2 and N_2 and (ii) 9970ppm H_2/air and air at 132 . The inset is the enlarged view upon exposure to a 9970ppm H_2/N_2 gas.

Fig. 3 shows the relationship between the drain current variation and the hydrogen concentration in N_2 environment at temperatures from 30 to 160 . It is clear that the sensing signal in the N_2 environment is logarithmically proportional to the hydrogen concentration. Furthermore, a significant hydrogen sensitivity ratio of $S = 0.137$mA/ppm H_2/N_2 is obtained at 30 . When the temperature is increased to 160 , the S value is decreased to 0.058mA/ppm H_2/N_2. This is because the hydrogen adsorption process of the studied device is an exothermic reaction.

The hydrogen current–responses at 132 with two different testing systems including (i) 9970ppm H_2/N_2 and N_2 and (ii) 9970ppm H_2/air and air are shown in Fig. 4. Obviously, the detecting signal can be recovered to 5.10 mA in a N_2 environment. Over a high temperature range, hydrogen atoms may gain much high energy to facilitate the surface chemical reaction. As seen in the inset of Fig. 4, the desorption process in a N_2 environment can be divided into three regions. Region I is defined as the initial stage. As the hydrogen gas is shut off and the carrier gas of N_2 is introduced, the equilibrium of hydrogen concentration between the Pd metal surface and the Pd-oxide interface is suddenly broken. A sharp drop of detecting signal is observed. As the time goes on, the detecting signal will enter into region II which is defined as the accumulation stage. In this region, more hydrogen atoms are desorbed. Due to the slow recombination of hydrogen atoms, the accumulation of hydrogen atoms on the Pd metal surface is developed. This may result in the reduction of recovery rate. In region III, defined as the revived stage, the amount of adsorbed hydrogen atoms on the Pd metal surface is increased with the time. This may increase the binding opportunities for these hydrogen atoms, whi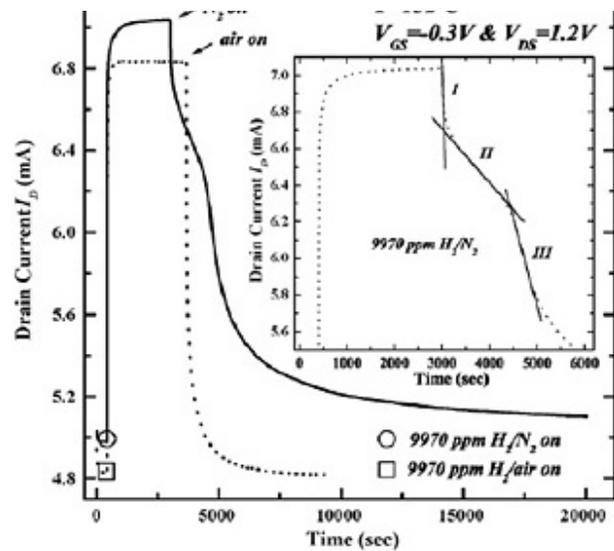ch certainly increases the recovery rate.