Hydrogen sensing properties of a metamorphic high electron mobility transistor

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Hydrogen sensing properties of a metamorphic high electron mobility transistor (MHEMT) are studied and presented. This MHEMT-based sensor exhibits good pinch-off characteristics upon exposing to hydrogen gases. Besides, the current variation and threshold voltage shift of the studied device reveal larger response under hydrogen-containing conditions. The studied device shows fast responses and exhibits a large current variation magnitude of the order of milliampere and a relatively low sensitivity due to the high baseline current. Based on the Langmuir isotherm, experimental current responses are consistent with the simulated curve. This indicates that the surface reaction is the rate limited factor for this hydrogen adsorption reaction. © 2009 American Institute of Physics. [DOI: 10.1063/1.3052698]

Due to the increasing requirement of hydrogen, the development of the hydrogen sensor has become an important issue over the past years. Semiconductor-type hydrogen sensors have attracted considerable attention due to their compatibility with conventional fabrication process. Previously, the Schottky diode-based hydrogen sensors were widely studied and reported.¹⁻³ With the rapid progress in epitaxial technology, more complicated device structures can be achieved. Electron devices, for instance, the light emitting diode and high electron mobility transistor (HEMT) largely require mature and high-quality epitaxy. Recently, much attention has been paid to HEMT-based hydrogen sensors.⁴⁻⁵ Yet, the report related metamorphic HEMT (MHEMT)-based hydrogen sensors has not been found. Compared to the InP HEMT, the MHEMT provides the merits of low cost, less fragility, and large substrate size.⁶ The high indium content and large bandgap discontinuity at channel layer can largely increase the electron mobility and thus lead to good electron transport characteristics.⁷ In this work, a hydrogen sensor based on an InAlAs-MHEMT with a Pd metal gate is fabricated and demonstrated. This MHEMT-based sensor exhibits a larger current variation and voltage shift as compared with previous reports.⁸⁻⁹

The epitaxial structure was grown on a GaAs substrate by a metal organic chemical vapor deposition system. The epitaxial layers consisted of a 2 μm thick indium-graded In₀.₄₂Al₀.₅₈As metamorphic buffer layer, a 3000 Å thick In₀.₄₂Al₀.₅₈As barrier layer, a 200 Å thick In₀.₄₃Ga₀.₅₇As channel layer, a 50 Å thick In₀.₄₂Al₀.₅₈As spacer layer, a single δ-doped sheet, a 200 Å thick In₀.₄₂Al₀.₅₈As Schottky contact layer, and a 50 Å thick n⁺-In₀.₄₃Ga₀.₅₇As cap layer. The metamorphic buffer layer can accommodate the lattice mismatch between the GaAs substrate and InGaAs channel layer. The large bandgap of InAlAs can supply good Schottky characteristics. Mesa isolation was made by wet chemical etching (H₃PO₄:H₂O₂:H₂O). Ohmic contacts were formed on the cap layer by evaporating AuGe/Au metals, followed by a 603 K annealing for 15 s. Furthermore, a highly selective PH-adjusted solution (succinic acid: H₂O₂:NH₄OH) was employed to remove the cap layer for gate recess. Finally, the gate Schottky contact was achieved by evaporating the Pd catalytic on the 200 Å undoped In₀.₄₂Al₀.₅₈As Schottky layer. The gate pattern was 1 × 100 μm² in dimension.

Figure 1 illustrates the typical drain-source current-voltage (I-V) characteristics of the studied Pd/InAlAs MHEMT hydrogen sensor at 303 K. All I-V curves reveal good pinch-off, saturation characteristics, and normally on field-effect transistor (FET) characteristics. Clearly, the current response increases with increasing hydrogen concentration. The large current variation can be attributed to the amplification behavior of the transistor. A largest current variation value of about 2.2 mA is observed at V_DS=1.5 and V_GS=0 V upon exposing to a 1% H₂/air gas. The current variation of the studied device is much larger than that of other HEMT-based hydrogen sensors.⁸⁻⁹ The current varia-

FIG. 1. Typical drain-source current-voltage (I-V) characteristics of the studied Pd/InAlAs MEMT hydrogen sensor under different hydrogen gases at 303 K.
function of hydrogen concentration. The concentration gradients of hydrogen atoms between the Pd surface and Pd/InAlAs interface drive hydrogen atoms to diffuse through the Pd metal bulk to the Pd metal/semiconductor interface. Then, the internal electric field polarizes the hydrogen atoms and thus forms a dipole layer at the Pd/InAlAs interface. The density of the two-dimensional electron gas (2-DEG) at the channel layer is increased by the reduction in the depletion region due to dipole formation. The increased 2-DEG leads to the increase in current variation when exposing to hydrogen gases. As compared to the FET sensor reported by Andrei et al., the proposed device exhibits a large current variation magnitude of the order of milliamperes. However, the reported FET sensor has a relatively high sensitivity due to its low baseline current.

Figure 2 illustrates the maximum transconductance \( g_{m,\text{max}} \) and threshold voltage \( V_{th} \) as a function of hydrogen concentration at 303 K. The magnitude of the threshold voltage \( V_{th} \) increases by the increase in hydrogen concentration. The decrease in the \( V_{th} \) magnitude with hydrogen concentration can be ascribed to the increased density of 2-DEG at the channel layer. Therefore, more negative gate bias is needed to deplete the channel layer. The studied device shows a significant threshold voltage shift \( \Delta V_{th} \) of 260 mV upon exposing to a 1% \( \text{H}_2/\text{air} \) gas. The maximum magnitude of \( \Delta V_{th} \) for the Pd MHEMT-based hydrogen sensor is larger than that of GaAs (60 mV) and AlGaAs (90.5 mV) HEMT-based ones. Besides, the magnitude of \( V_{th} \) also shows an interesting and relatively linear trend under the hydrogen concentration from 50 to 1000 ppm \( \text{H}_2/\text{air} \). Thus, the studied Pd/InAlAs MHEMT hydrogen sensor exhibits good linearity upon exposing to intermediate-concentration hydrogen gases. Figure 2 also reveals that the maximum transconductance \( g_{m,\text{max}} \) decreases with increasing hydrogen concentration. The \( g_{m,\text{max}} \) is slightly decreasing with increasing hydrogen concentration, which suggests that the gate control ability slightly decreases with the increased hydrogen concentration.

The transient response curves of the studied device at 363 K are shown in Fig. 3. Apparently, the current variation increases with the hydrogen concentration. Compared to the Pt-FET hydrogen sensor, the studied device has relatively short response times under the same testing conditions. For example, under exposing to a 50 ppm \( \text{H}_2/\text{air} \) gas at 363 K, the response time of the studied device is 30 s, which is remarkably shorter than that of the reported sensor (100 s).

The overshooting phenomenon is observed while the hydrogen concentration is larger than 50 ppm \( \text{H}_2/\text{air} \). This phenomenon can be attributed to the hydrogen-oxygen interaction at high temperatures, which produces water molecules and hydroxy.

The Pd surface is covered with oxygen molecules at air atmosphere. All hydrogen molecules impinging on the catalytic Pd metal react with oxygen molecules to form the hydroxyl. Subsequently, the hydroxyl reacts with the hydrogen atoms to form water molecules at higher temperatures. Therefore, the overshooting phenomenon is observed due to the formation of water molecules. The abnormal current variation is not observed for the introduction of 50 ppm \( \text{H}_2/\text{air} \) gas. This indicates that the produced water is negligible under exposing to low-concentration hydrogen gases.

The reactions of hydrogen adsorption can be briefly expressed as

\[
\text{H}_2 \xrightleftharpoons[d_1]{c_1} 2\text{H}_a, \tag{1}
\]

\[
\text{O}_2 + 2\text{H}_a \xrightleftharpoons[d_2]{c_2} 2\text{OH}_a, \tag{2}
\]

where \( c_1 \) and \( c_2 \) are the forward reaction constants, \( d_1 \) and \( d_2 \) are the constants for reverse reactions, \( \text{H}_a \) is the hydrogen atom, and \( \text{OH}_a \) is the hydroxyl, respectively. The reverse reactions of Eqs. (1) and (2) are neglected to simplify the analyses. Thus, the relation between the steady-state current \( I_{g,\text{st}} \) and hydrogen partial pressure \( P_{\text{H}_2} \) can be expressed as

\[
\log \left( \frac{I_{g,\text{st}}}{I_o} \right) = \left( \frac{\mu}{e} \right) \left( \frac{c_1 P_{\text{H}_2}}{2 c_2 P_{\text{O}_2}} \right)^{1/2} N_o \left( 1 + \frac{c_1 P_{\text{H}_2}}{2 c_2 P_{\text{O}_2}} \right)^{1/2} V_T, \tag{3}
\]

where \( I_o \) is the steady-state current in air ambiance, \( \mu \) is the dipole moment, \( e \) is the permittivity of InAlAs, \( P_{\text{O}_2} \) is the oxygen partial pressure, \( N_o \) is the total number of adsorption sites at the interface, and \( V_T \) is the thermal voltage. Equation (3) is a Langmuir-type equation. Figure 4 illustrates the logarithmic value of the ratio between \( I_{g,\text{st}} \) and \( I_o \) versus the square root of hydrogen.
partial pressure ($\sqrt{P_{H_2}}$) at 363 K. Although the overshooting phenomenon is revealed in Fig. 3, the simulated curve is still consistent with experimental results. The consistence between the experimental data and simulation indicates that the adsorption of hydrogen is dominated by the surface reaction i.e., the surface reaction is the rate-limited factor of this reaction.14

In conclusion, an interesting hydrogen sensor based on a MHEMT with a Pd/InAlAs structure is fabricated and demonstrated. The studied MHEMT sensor exhibits the larger signal response in terms of current variation and voltage shift as compared with previous reports. Based on the Langmiur isotherm, the experimental current responses are consistent with the simulated curve. This result indicates that the surface reaction is the rate limited factor for this hydrogen adsorption reaction. Consequently, based on the sensing capability and its well-known high-frequency properties, the studied Pd/InAlAs MHEMT hydrogen sensor provides the promise for the integration between high-performance hydrogen sensors and microwave devices.

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