

Pt/AlGaIn/GaN Heterojunction Field Effect Transistor Hydrogen Sensors at High Temperatures

The rapid growth of the sensor market in recent years has stimulated the development of chemical sensor technology for applications such as aerospace aircrafts, factory automation, chemical reactor processing, and industrial monitoring. For these applications, sensors should have high-temperature durability, long-term stability, high sensitivity, and repeatability. Silicon-based devices have been extensively studied for gas sensor applications since 1975, but they cannot sustain very high temperatures. Wide band gap compound semiconductor materials, including SiC and GaN, have been candidates for high-temperature gas sensing applications. Especially in an AlGaIn/GaN heterostructure, the polarization-induced two-dimensional electron gas (2DEG) concentration at the AlGaIn/GaN interface is extremely sensitive to surface states. Any polarity changes on the surface by adsorption of gases or biomolecules or pressure change would affect the surface potential and modulate the 2DEG density. Therefore, devices on AlGaIn/GaN heterostructures have great potential for chemical gas sensing in harsh environments. One of the great advantages of GaN-based solid-state sensors is the ability to integrate multiple sensors with signal processing circuits on the same wafer, resulting in small area, low power consumption and cost efficiency. In this work, Pt/AlGaIn/GaN heterojunction field effect transistors (HFETs) with greatly enhanced device sensitivity and detection limit have been demonstrated. In these devices, the drain channel current is monitored for gas chemical sensing. The dependence of hydrogen detection sensitivity on applied gate and drain biases is investigated.

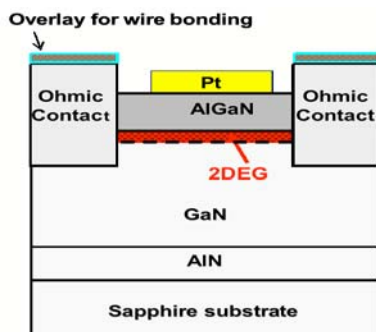


Figure 1. Device cross-section structure of Pt/AlGaIn/GaN heterostructures field-effect transistors for gas sensors

Sensing characteristics of AlGaIn/GaN HFETs at high temperatures

AlGaIn/GaN HFETs with Pt catalytic metal were fabricated and characterized from 25°C to 800°C for H₂ sensing. The device cross-section structure is shown in Figure 1. H₂ sensing measurements were carried

out in a small closed chamber connected to a gas mixer for controlling the hydrogen concentrations in nitrogen.

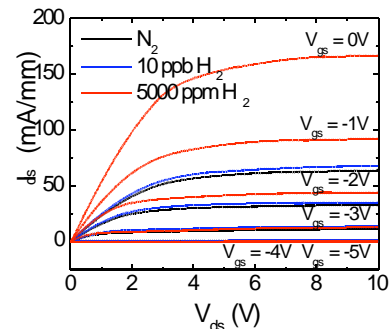


Figure 2. The I_{ds} - V_{ds} characteristics of Pt/AlGaIn/GaN HFETs at 600°C in N₂, 10 ppb, and 5000 ppm H₂/N₂. V_{gs} is varied from 0 V to -5 V at a step of -1 V.

Figure 2 shows the drain current (I_{ds}) – voltage (V_{ds}) characteristics of Pt/AlGaIn/GaN HFETs at 600°C in N₂, 10 ppb, and 5000 ppm H₂/N₂, respectively. The gate bias (V_{gs}) is varied from 0 V to -5 V at a step of -1 V. The drain current at a fixed V_{gs} increases when the device is exposed to the H₂-containing ambients and is quantitatively modulated by the H₂ concentration down to 10 ppb, indicating a higher 2DEG concentration in H₂. The device pinch-off voltage decreases from -4 V in N₂ to -5 V in 5000 ppm H₂/N₂. For the dependence of sensitivity on gate bias at a fixed V_{ds} , Figure 3 shows the sensitivity, I_{ds} , and transconductance (g_m) as a function of V_{gs} at $V_{ds} = 1$ V and a temperature of 600°C in 5000 ppm H₂/N₂. Here, the sensitivity is defined as the ratio of drain current change and the drain current in N₂ ambient at the same condition. The results clearly show that the sensitivity is strongly dependent on V_{gs} and peaks at $V_{gs} = -3.57$ V in 5000 ppm H₂/N₂. Interestingly, the gate bias, which gives the highest sensitivity at a fixed V_{ds} , called the peak gate bias ($V_{gs,peak}$), is the same as the threshold voltage (V_{th}) in H₂ containing ambient, where V_{th} is defined as the intercept to V_{gs} axis of the linear extrapolation of drain current at the gate bias for peak g_m . The V_{th} is shifted from -2.81 V in N₂ to -3.57 V in 5000 ppm H₂/N₂. At the bias point of $V_{gs,peak}$, the device in the N₂ ambient is operated in the sub-threshold regime and right at the off-state. So, at this bias, a small change of surface potential would turn on the channel because of hydrogen dissociation and dipole layer formation at the catalytic metal and AlGaIn interface, leading to dramatically enhanced sensitivity.

Figure 4 presents the effect of V_{ds} on the sensitivity at 600°C in 5000 ppm H₂/N₂ at V_{gs} near the $V_{gs,peak}$, $V_{gs} = -3.4$ V to -3.6 V at a step of -0.05 V. Clearly, at a fixed V_{gs} , the sensitivity has a peak value at a certain drain bias

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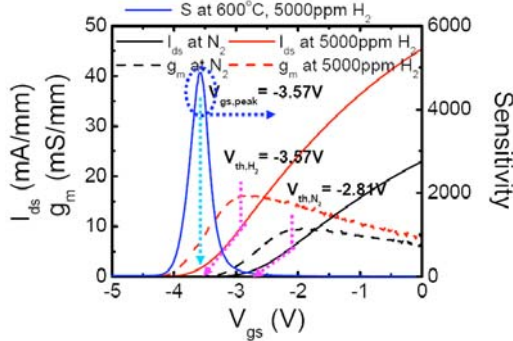


Figure 3. I_{ds} , g_m , and the sensitivity versus V_{gs} of Pt/AlGaN/GaN HFETs at $V_{ds} = 1$ V and a temperature of 600°C in 5000 ppm H_2/N_2 .

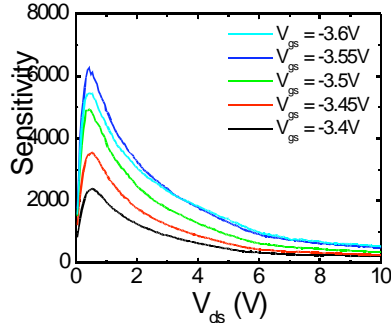


Figure 4. The sensitivity of HFETs in 5000 ppm H_2/N_2 as a function of V_{ds} at 600°C and different V_{gs} . The range of V_{gs} is from -3.4 V to -3.6 V at a step of -0.05 V.

called peak drain bias ($V_{ds,peak}$). At $V_{gs} = -3.55$ V and $V_{ds,peak} = 0.45$ V, the device exhibited a sensitivity of as high as 6270. As the gate bias changes from -3.4 V to -3.6 V, the $V_{ds,peak}$ shifts from 0.55 V to 0.45 V. It is interesting to notice that $V_{ds,peak}$ is almost the same with the knee voltage (V_{knee}) in the H_2 -containing ambient, where V_{knee} is determined as the corresponding drain bias at the intercept of linear extrapolations of drain currents in the linear region and in the saturation region. In 5000 ppm H_2/N_2 , V_{knee} shifts from 0.55 V to 0.44 V as V_{gs} changes from -3.4 V to -3.6 V. The reason of sensitivity peaking at V_{knee} in the H_2 containing ambient is that the drain current gets saturated at a slightly higher drain bias in H_2 at a fixed gate bias, or in other words, the device has a higher V_{knee} compared with that in N_2 .

Figure 5 shows the peak sensitivity of HFETs at $V_{gs,peak}$ and $V_{ds,peak}$ as a function of temperature at different H_2 concentrations. At a fixed temperature, the sensitivity increases with the H_2 concentration. At a fixed H_2 concentration, the sensitivity increases almost exponentially with temperature up to 600°C . The improvement of sensitivity at high temperatures is attributed to the more effective dissociation of hydrogen molecules in the catalytic film. The device sensitivity saturates at 600°C . The reason for this is unknown and

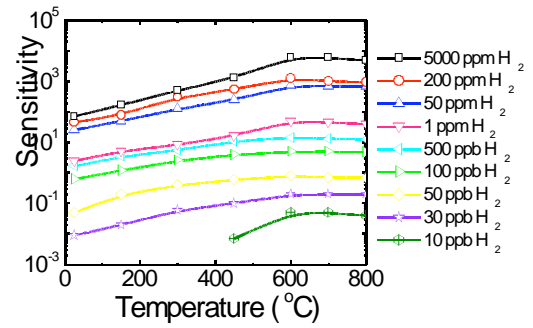


Figure 5. The sensitivity of HFETs in 5000 ppm H_2/N_2 as a function of V_{ds} at 600°C and different V_{gs} . The range of V_{gs} is from -3.4 V to -3.6 V at a step of -0.05 V.

under investigation. However, up to 800°C , the test was completely repeatable even after more than 30 hours of testing. This indicates that the devices are reliable for H_2 sensing up to 800°C . At high temperatures, especially at 1000 ppm or higher H_2 concentrations, the peak sensitivity of HFETs at $V_{gs,peak}$ and $V_{ds,peak}$ is more than three orders higher than their sensitivity at $V_{gs} = 0$ V and the sensitivity of Schottky diodes. At 5000 ppm H_2/N_2 , the values of device sensitivity are 71 at 25°C , 514 at 300°C , and 6251 at 600°C at $V_{gs,peak}$ and $V_{ds,peak}$, while the values are 0.3, 0.8, and 2 at $V_{gs} = 0$ V and $V_{ds} = 1$ V, respectively.

Publications

1. Junghui Song, Jeffrey S. Flynn, George R. Brandes, and Wu Lu, "AlGaIn/GaN Schottky diode hydrogen sensor performance at high temperatures with different catalytic metals," *Solid State Electronics*, vol. 49/8, pp. 1330-1334, 2005.
2. Junghui Song, Jeffrey S. Flynn, George R. Brandes, and Wu Lu, "Pt-AlGaIn/GaN Schottky diodes operated at 800°C for hydrogen sensing," *Applied Physics Letters*, vol. 87/13, pp. 133501-133501-3, 2005.
3. Junghui Song, Jeffrey S. Flynn, George R. Brandes, and Wu Lu, "Polarity detectable chemical sensors based on AlGaIn/GaN heterostructures field effect transistors," *Applied Physics Letters*, vol. 89/22, pp. 223503, 2006.
4. Junghui Song and Wu Lu, "Thermodynamic and kinetic analysis of hydrogen sensing in Pt/AlGaIn/GaN Schottky diodes at high temperatures," submitted to *IEEE Sensors Journal* in 2007.
5. Junghui Song and Wu Lu, "Pt/AlGaIn/GaN heterojunction field effect transistor hydrogen sensors with improved detection limit and sensitivity," submitted to *IEEE Electron Device Letter* in 2008.
6. Junghui Song and Wu Lu, "The influence of gate and drain bias on improving device sensitivity of Pt/AlGaIn/GaN heterojunction field effect transistor hydrogen sensors," *Invention Disclosure* submitted.