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AlGaN/GaN HEMT micro-sensor technology for gas sensing applications

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Abstract
Wide bandgap gallium nitride material has highly favorable electronic properties for next generation power and high frequency electronic devices. A less widely studied application is highly miniaturized chemical and gas sensors capable of operating in harsh environment conditions. In this work we present our recent developments on design, fabrication and testing of AlGaN/GaN high electron mobility transistor (HEMT) based sensors for detection of various gases. First, the method of as-fabricated device baseline value stabilization is demonstrated. Secondly, the impact of sensor design is discussed with the emphasis on gate electrode geometry optimizations to enhance sensing performance. Then we present the sensing characteristics of Pt-HEMTs towards H_2S and compare them to H_2 and NO_2. Finally we demonstrate recent results of NO_2 detection with Ti/Au based HEMT sensors, which are superior to those using Pt based devices.

1. Introduction
Monitoring and detection of trace concentrations of various gases, vapors and volatile organic compounds is of increasing demand for environmental monitoring and industrial applications. Air quality analysis, gas leakage detection, management of production bi-products, food spoilage prevention and insuring worker safety are some of the fields where gas and chemical compound sensing is essential. A wide range of transducers and materials have been developed for sensor applications such as electrochemical [1], optical [2], surface acoustic wave [3], metal-oxide conductometric devices [4].

Field-effect based sensors such as MOS capacitors, Schottky diodes and transistors are of particular interest for a wide variety of detection applications. The advantageous features of these devices include the potential for high degree of miniaturization, high-volume manufacturing capability, by utilizing established semiconductor micro-fabrication techniques, and compatibility with a wide range of sensing materials such as catalytic metals, oxides, polymers or nano-materials. The first results of hydrogen sensing using a silicon MOSFET with a catalytic Pd gate were reported by Lundström [5]. Since then, FET type sensors have been further improved with device structures such as suspended gate and floating gate [6, 7]. Due to the narrow energy bandgap of Si, the operating temperature is limited to 200 °C [8]. Higher operating temperatures are frequently necessary to enhance the gas detection properties such as selectivity, sensitivity and response/recovery times. The application of wide bandgap (3.4 eV) gallium nitride (GaN) semiconductor for FET sensors is highly promising. GaN has been demonstrated to be highly stable in corrosive and high temperature environments [9]. Furthermore high electron mobility transistors (HEMT) formed by AlGaN/GaN heterojunction possess a high electron concentration channel (2DEG) close (15 – 30 nm) to the surface, that is very sensitive to adsorbed gas molecules or atoms. Previous results have demonstrated the application of GaN and AlGaN/GaN Schottky diodes and HEMTs with catalytic metal or metal-oxides as sensing layers to sense H_2, NH_3 O_2, NO_2 and other gases [10, 11].

In this report, the results of optimizing gas sensors based on AlGaN/GaN HEMTs fabricated on commercially available substrates are presented. Method of stabilizing the device baseline by using prolonged burn-in at elevated temperature is shown. The impact of sensor layout design on device performance is demonstrated. Additionally, experimental results of detecting H_2, H_2S and NO_2 are demonstrated for sensors using Pt and Ti/Au as sensing electrodes.

2. Materials and Methods
The epitaxial material used for sensor fabrication was purchased from a commercial vendor and had layer structure equivalent to that used for power HEMT fabrication. This structure was grown on 2-inch c-plane sapphire substrates by Metal-organic chemical vapor deposition (MOCVD) and consisted, from top to bottom,

of 1 nm thin undoped GaN cap layer, 21 nm AlGaN barrier layer with 26 % Al content, 1 nm AlN spacer and 1.8 µm GaN buffer layer. Fabrication started with wet chemical cleaning and device isolation by 90 nm deep ICP etching. Afterwards source/drain contact regions were lithographically defined. After a 1 min dip in dilute HCl solution, Ti/Al/Ti/Au (20/110/40/50 nm) metal stack was e-beam evaporated and patterned by lift-off. Ohmic contacts were rapid thermal annealed at 870 °C for 47 s in N_2 ambient. The contact resistance, extracted from circular transmission line measurements, was 0.7 Ω×mm. The gate electrode was then formed by e-beam evaporation and lift-off. Two types of gates were studied here for different gas detection, a 10 nm Pt and a Ti/Au (5/10 nm). Probing and wirebonding metal stack of Ti/Au (30/300 nm) was evaporated and patterned. The devices were then passivated with 500 nm of PECVD SiN_x, which was patterned by RIE and BOE etching to open the sensing area and bonding pads. A schematic cross-sectional view of the fabricated HEMT sensor is shown in Figure 1.

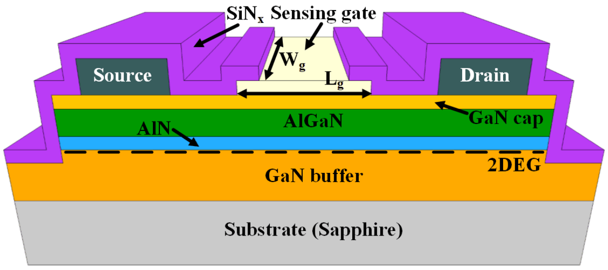

Figure 1. Cross-sectional schematic of AlGaN/GaN HEMT sensor.

Sensor testing was performed inside an enclosed chamber with temperature and humidity control. Test gases diluted in N_2 were supplied using mass flow controllers operated by dedicated PC software and dry synthetic air was as background gas. Electrical sensor measurements were performed using a pair of Keithley 2450 source meters.

3. Results and Discussion

3.1 Baseline stabilization

As fabricated FET type sensors frequently experience noticeable drift of their baseline signal value, which can result in unstable operation and necessity for frequent recalibration. A burn-in process at elevated temperature is utilized to obtain a more stable baseline value prior gas measurements. Figure 2 shows continuous drain current measurement of Pt-HEMT sensor over 12 hour burn-in in dry air. It is observed that during first 3 hours there is significant instability of the signal, followed by gradual downwards drift until hour 9. The signal starts to stabilize approaching hour 10 and remains at a fairly

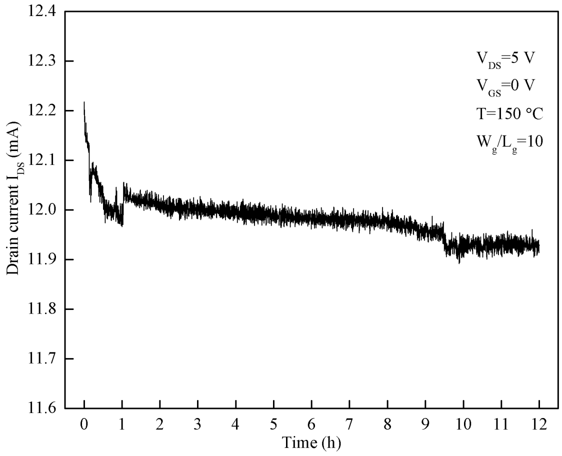

Figure 2. Continuous drain current (I_{DS}) measurement during 12 h burn-in period.

constant value, ready for gas testing.

3.2 Sensor layout optimization

The output drain current (I_{DS}) and transconductance (g_m) magnitude of FET and HEMT are directly proportional to the gate electrode width (W_g) and length (L_g) ratio (W_g/L_g). We have designed sensors with open gate dimension ratios of 0.25, 0.5, 5 and 10 (Figure 3) to

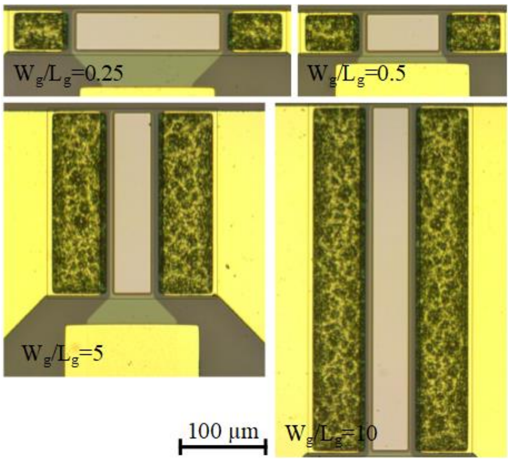

Figure 3. Micrographs of fabricated sensors with different W_g/L_g ratios.

compare sensing performance of H_2. The output (I_{DS}-V_{DS}) and transfer (I_{DS}-V_{GS}) characteristics of each geometry at 200 °C in dry air are shown in Figure 4 (a) and (b) respectively. Clearly the drain current value increases from 0.43 mA to 9.17 mA (at V_{GS}=0 V, V_{DS}=5 V) with larger W_g/L_g. This current is the baseline value of the sensor in air ambient ($I_{DS,air}$). The maximum transconductance (g_m) value increased from 0.26 mS to 5.84 mS. Larger g_m results in higher drain current variation with small changes in gate voltage. Figure 5 depicts the transient response characteristics at V_{DS}=5 V and V_{GS}=0 V for all tested geometries. The sensing signal variation ($\Delta I = I_{DS,H_2} - I_{DS,air}$) has risen from 0.012

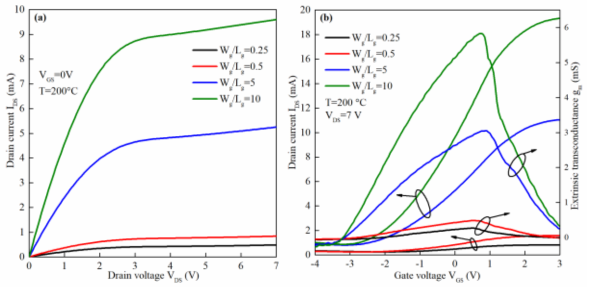

Figure 4. (a) Output and (b) transfer characteristics of the tested sensor layout geometries at 200 °C.

mA for W_g/L_g=0.25 to 0.72 mA for W_g/L_g=10 upon introduction of 500 ppm H_2, a 60x increase. It is evident that larger gate electrode ratios are necessary to obtain a higher signal variation, sensing sensitivity and to lower the detection limits [12]. Due to higher baseline current levels the power consumption of the sensors increased, however it can be further modified via gate bias voltage.

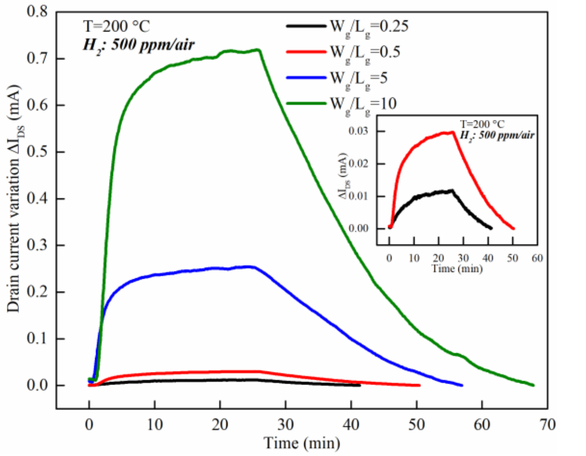

Figure 5. Transient response characteristics of Pt-HEMT sensors with different gate electrode *W_g/L_g* ratios. The inset shows enlarged characteristics for 0.25 and 0.5 ratio sensors.

3.3 H_2S Detection Properties

Hydrogen sulfide (H_2S) is poisonous, flammable gas which can be lethal upon inhalation of low concentration of 500 ppm. It is a by-product of several industrial manufacturing processes and petroleum production.

AlGaN/GaN Pt-HEMT sensors were investigated for detection low ppm levels of H_2S. Figure 6 shows the output (a) and transfer (b) characteristics upon exposure to H_2S. The detection mechanism is based on the catalytic dissociation of the gas molecules to H and S atoms on the Pt surface. The charged hydrogen ions then rapidly diffuse thought the metal towards interface with the semiconductor where a dipolar layer is formed. These interfacial charges cause a reduction of the metal work function proportional to analyte concentration, which leads to the lowering of the Schottky barrier. The

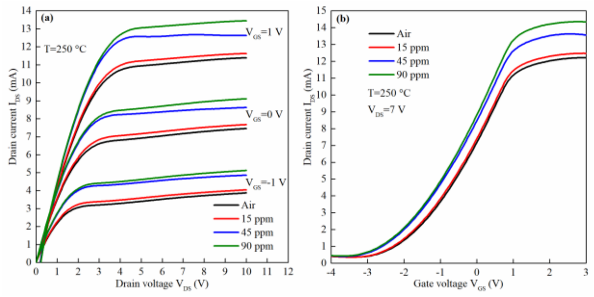

Figure 6. (a) Output and (b) transfer characteristics of the Pt-HEMT sensor exposed to H_2S at 250 °C.

resulting increase of drain current under the same gate bias conditions as well as negative shift of the transfer curves is therefore observed. Upon exposure to 90 ppm H_2S the drain current increased by 2.1 mA at V_{GS}=1 V, V_{DS}=5 V. The corresponding gate voltage shift was -0.38 V at I_{DS}=5 mA.

The repeatability of the sensor signal towards H_2S is evaluated by transient response measurements of 3 cycles of 90 ppm H_2S exposure and air purge (Figure 7). Excellent response and recovery was observed that suggesting reliable sensing performance.

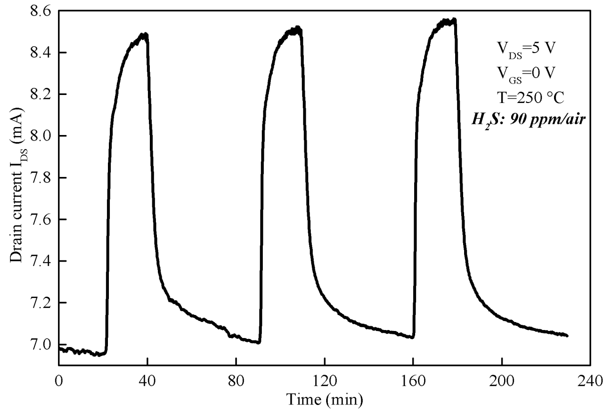

Figure 7. Transient repeatability characteristics of Pt-HEMT sensors to 3 cycles of 90 ppm H_2S.

Catalytic gate FETs are widely studied for the detection of H_2. To compare the Pt-HEMT selectivity between H_2S, H_2 and NO_2 transient responses were measured for the same concentration of 60 ppm in dry air (Figure 8). Clearly H_2S had the highest response signal (*ΔI*) of 1.18 mA, while for H_2 it was 0.32 mA and NO_2 -0.034 mA. The 3.7x difference in response between H_2S and H_2 is likely due to differences in sticking coefficient between the gases and Pt at the tested temperature. Furthermore O adsorb on the Pt surface and occupy bonding sites of H_2. During H_2S dissociation the sulphur atoms can form SO_2 with the adsorbed oxygen and desorb from the surface thereby freeing up additional bonding sites for H. Further studies of H_2S and H_2 sensing under different

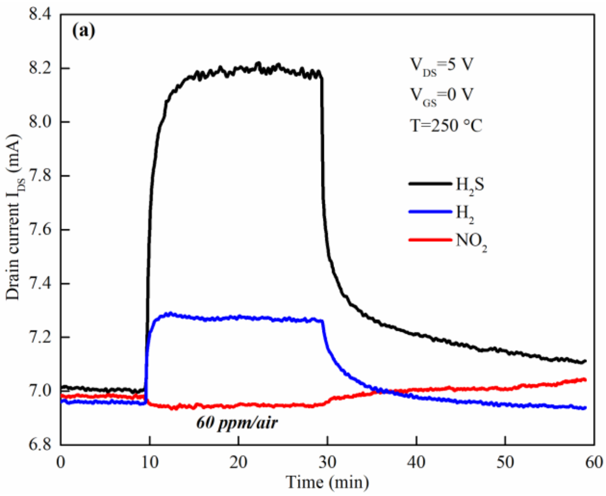

Figure 8. Transient response characteristics of Pt-HEMT sensors towards H_2S, H_2 and NO_2 at 250 C.

ambient gases are necessary to gain more insight to the observed response differences. The response towards NO_2 was very low and of opposite nature, which is consistent with previous studies.

3.4 NO_2 detection with Ti/Au-gated HEMT

Nitrogen dioxide (NO_2) is a toxic gas produced by combustion processes and is therefore a major environmental pollutant which causes respiratory problems even at low ppm concentrations.

Detection of low NO_2 concentrations was investigated using Ti/Au-gated HEMT sensors. The thin Ti layer was used to improve Au adhesion to GaN. We have observed that after initial exposure to higher (hundreds of ppm) NO_2 concentrations the sensors were able to detect low ppm concentrations of NO_2 at 150 °C as demonstrated in Figure9. The obtained response is different from that of

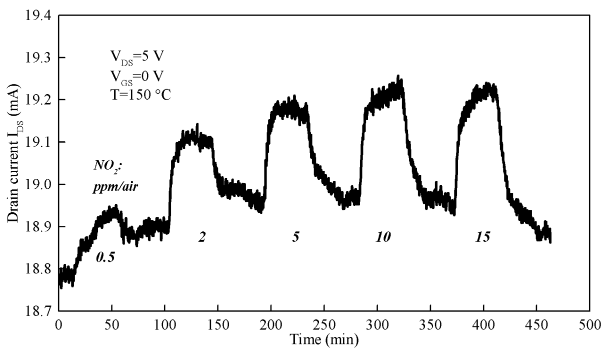

Figure 9. Transient response characteristics of Ti/Au-HEMT upon injection and purge of NO_2 in dry.

Pt-HEMTs as the current values increased upon gas injection. The detection mechanism of these devices is still under study, however initial results suggest superior sensitivity to NO_2 compared to Pt-HEMT sensors.

4. Summary

GaN based HEMTs are a highly promising technology for micro-scale, low power and high sensitivity sensor development due to highly favorable material and transducer properties. We have reported the latest work conducted in our group on fabrication and testing of these sensors. The importance of device burn-in was demonstrated. The impact of device geometry on sensing performance was evaluated with the results indicating that higher W_g/L_g ratios allow larger signal variation, however the power consumption is also increased. Furthermore, comparison of H_2S and H_2 sensing properties with Pt-HEMTs was demonstrated, indicating that there is a large variation in response under same gas concentrations. Finally, the successful detection of NO_2 was demonstrated down to 500 ppb in air using Ti/Au-gated HEMT sensors.

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