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Pt-AlGaN/GaN HEMT-sensor layout optimization for enhancement of hydrogen detection

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***Abstract*—This paper reports on the layout optimization of Pt-AlGaN/GaN HEMT-sensors for enhancing hydrogen sensor performance. Sensors with gate width and length ratios W_g/L_g from 0.25 to 10 were designed, fabricated and tested for the detection of hydrogen gas at 200 °C. Sensitivity, sensing current variation and transient response are directly related to the sensor gate electrode W_g/L_g ratio. The obtained results demonstrated a 217 % increase in sensitivity and 4630 % increase in sensing current variation at 500 ppm H_2 for a W_g/L_g from 0.25 to 10. In addition, the detection limit was lowered to 5 ppm. Transient characteristics demonstrated faster sensor response to H_2, but slower recovery rates with increasing ratio.**

Keywords—GaN, AlGaN, HEMT, H_2 sensor, sensor layout, high temperature

I. INTRODUCTION

To date solid-state gas sensors have found applications in air quality monitoring, automotive exhaust gas pollutant monitoring, industrial process leak detection and exhaled breath systems [1]. Gas sensitive field effect transistors (FET) have been gaining extensive interest [2] for integrated, low power, low cost, miniature sensing applications.

AlGaN/GaN Schottky diode and high electron mobility transistor (HEMT) based sensors with catalytic metal sensing electrodes (anode or gate) have been previously demonstrated for detection of various gases e.g. NH_3, H_2S, H_2, NO_x, CO [3-6]. Gate electrode dimensions i.e. gate length (L_g) and width (W_g), directly impact the output characteristics of any FET device including HEMT, with larger W_g/L_g ratios leading to increased output current. AlGaN/GaN sensors with various gate electrode dimensions have been previously reported. Large gate area devices have been reported [3, 6, 7] with W_g/L_g ratios of 7, 1 or 5 respectively, while others [8, 9] used typical HEMT layouts with a few micron length and large width resulting in ratios on the order of 100. However the reasons for the design choices were not stated.

AlGaN/GaN-based hydrogen sensors have been particularly studied [7, 9-13], as H_2 is considered to be the source of renewable energy for future automotive, aerospace industries, fuel cells and as replacement of fossil fuels. H_2 is also widely used by chemical, manufacturing industries and in food processing [9]. It is therefore of great interest to investigate how layout design can be optimized in terms of sensitivity, signal variation magnitude and transient response. The effects of gate length for hydrogen sensor based on GaN MESFET were reported in [14]. The obtained results showed that longer gate and consequently larger gate area (lower W_g/L_g) resulted in higher variation of the sensing signal. However, unlike conventional FET, their device did not exhibit saturation across entire bias range and operated only in the resistive region. AlGaN/GaN HEMT sensor layout modeling was performed by [4] in order to determine the optimal design. The results suggested that there is a trade-off between device sensitivity (S) and absolute signal variation (ΔI) with larger W_g/L_g resulting in lower S and increased ΔI. Based on their model the optimal design was fabricated with gate dimensions 2 μm × 200 μm ($L_g \times W_g$) while different geometries were not tested.

In this work, we present the impact of Pt-AlGaN/GaN HEMT sensor geometry on sensitivity, sensing current variation and transient characteristics on H_2 detection. Sensors with W_g/L_g ratios of 0.25, 0.5, 5 and 10 have been designed, fabricated and tested to study the response to H_2. The effects of the layout variation on sensing sensitivity, signal variation and response time is reported and discussed.

II. SENSOR DESIGN AND FABRICATION

A simplified schematic view of the studied HEMT-sensor structure is shown in Fig. 1. The devices were fabricated on commercial epitaxial structures purchased from Nanowin that were grown by MOCVD on 2 inch sapphire wafers. The structure, starting from the substrates, consisted of a nucleation layer, 1.8 μm GaN buffer, 1 nm AlN interlayer, unintentionally doped 21 nm $Al_{0.26}Ga0_{.74}N$ barrier layer and 1nm GaN cap. The fabrication procedure started with wet cleaning of the wafers using acetone, isopropanol and DI water rinsing. Then, mesa etching was done using ICP etcher with BCl_3/Cl_2 plasma. Afterwards ohmic contact multilayer metal stack consisting of Ti/Al/Ti/Au with thickness of 20/110/40/50 nm was e-beam evaporated and patterned by lift-off. A 60 s dip in $HCl:H_2O$ was done shortly prior to loading the samples into the e-beam system to remove native oxide. Rapid thermal aneling was carried out

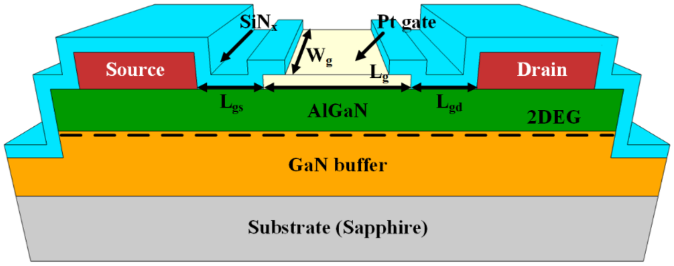


Fig. 1. Schematic representation of the HEMT-sensor used in this work.

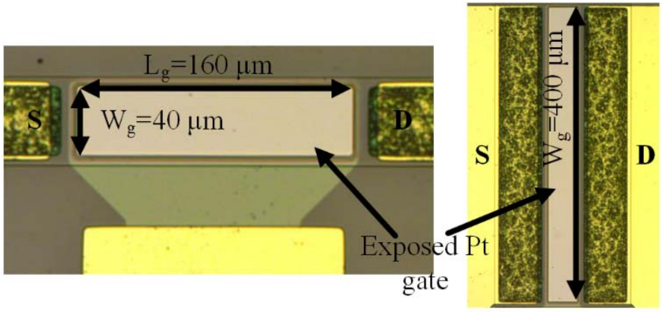
at 870 °C for 47 s in N_2. A 10nm Pt gate was then evaporated and patterned by lift-off, as the sensing electrode. The interconnection metal stack of Ti/Au 30/300 nm was evaporated and patterned followed by deposition of 500 nm PECVD SiN_x for device passivation. Finally, sensing gate and bond-pad windows were opened by combined RIE and BOE etching of the SiN_x.

The studied sensing gate geometries were designed by extending multiples of a 40 µm × 40 µm single cell either length ($W_g/L_g<1$) or width ($W_g/L_g>1$) wise. The fabricated devices with $W_g/L_g=0.25$ and $W_g/L_g=10$ are shown in fig. 2 (a) and (b). The gate-source (L_{gs}) and gate-drain (L_{gd}) distances were set at 6 µm for every device. Electrode ratios are defined based on the gate area exposed to the ambient, while the actual length footprint was 8 µm longer for all geometries, to allow edge encapsulation with SiN_x for improving gate electrode adhesion.

Diced devices were packaged and placed inside the gas mixing apparatus chamber (1.5 L volume) with temperature control, humidity monitoring and electrical feedthroughs for signal measurements. The testing temperature was fixed at 200 °C and the hydrogen concertation range was warried form 5 ppm to 500 ppm using mass flow controllers against dry synthetic (1:4 O_2:N_2) air as background gas. The gas flow rate was fixed at 300 sccm during all experiments. Sensor characteristics were measured using a pair of Keithley 2450 source meters controlled using PC software.

III. RESULTS AND DISCUSSION

The output characteristics (I_{DS}-V_{DS}) of the studied Pt-AlGaN/GaN sensors with different gate geometries exposed to H_2 gas at gate-source voltage $V_{GS}=0$ V are shown in fig. 3. Proper FET operation with clearly identifiable triode and saturation regions is sustained at the tested temperature. Drain current increase with increasing H_2 concentration is evident. This is due to catalytic dissociation of hydrogen molecules at the Pt-gate surface, followed by H atom diffusion to the metal-semiconductor interface where they form dipoles resulting in Schottky barrier lowering [8].



(a) (b)

Fig. 2. Fabricated HEMT sensors with $W_g/L_g=0.25$ (a) and $W_g/L_g=10$ (b).

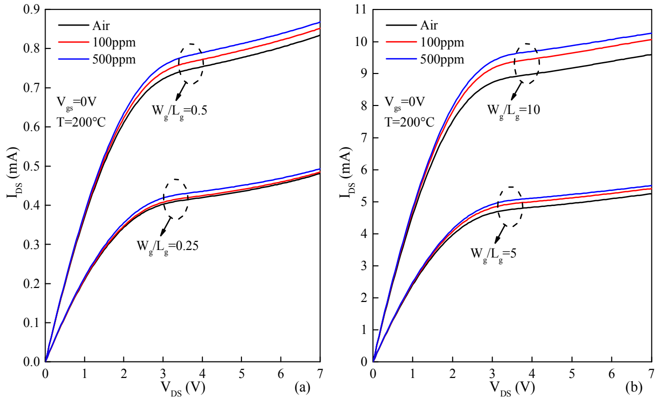


Fig. 3. Drain current versus drain-source voltage characteristics of HEMT-sensors with $W_g/L_g<1$ (a) and $W_g/L_g>1$ (b) upon exposure to H_2 gas in air.

To evaluate the impact of W_g/L_g ratio on the sensing characteristics of HEMT-sensors, drain current variation ($\Delta I=I_{DS,H2}-I_{DS,air}$) and sensitivity ($S=\Delta I/I_{DS,air}\times100\%$) at $V_{DS}=5$ V and $V_{GS}=0$ V were extracted and are shown in fig. 4. Both S and ΔI increased with increasing W_g/L_g. These findings might appear different from modeling results of [4], predicting a reduction in sensitivity with shorter L_g. In our case however, the higher S could be attributed to a less increase in baseline current value. ΔI increases due to a higher baseline I_{DS}. For 500 ppm H_2 concentration the S increased from 3.5 % for $W_g/L_g=0.25$ to 7.6 % for $W_g/L_g=10$ (217 % increase), while ΔI increased from 15 uA to 695 uA (4630 % increase). These results clearly demonstrate that larger W_g/L_g will result in superior DC performance of the HEMT sensor. One additional consideration for HEMT sensor design is that power consumption will increase due to higher current flowing through the HEMT with larger W_g/L_g. However the 3 terminal FET type sensor allows for tuning the operating point via gate and drain bias voltage to optimize the sensing or power consumption characteristics [7].

Transient characteristics of the studied geometries were tested in order to determine H_2 gas detection limits, as well as the response and recovery rates. Figure 5 shows I_{DS} variation as a function of time of the studied sensors with increasing H_2 concentration in the range of 5 ppm to 500 ppm. Gas was

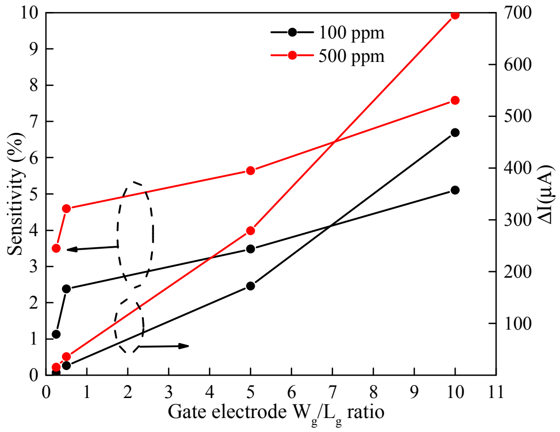


Fig. 4. HEMT-sensor sensitivity and sensing current variation dependency on gate electrode W_g/L_g ratio.

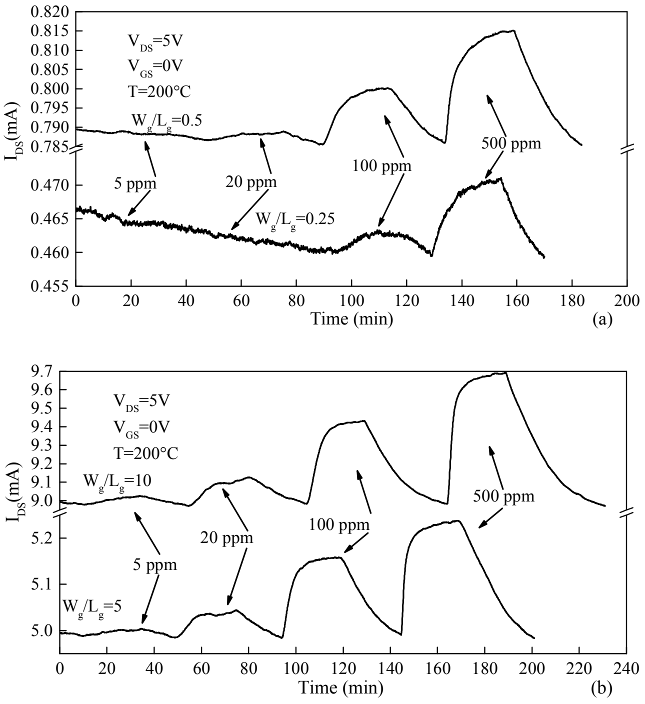


Fig. 5. Transient response of HEMT sensors with W_g/L_g<1 (a) and W_g/L_g>1 (b) to various H_2 gas concentrations.

supplied for 25 min for each injection cycle and purged with dry air until the signal recovered to the baseline level. Structure with W_g/L_g=0.25 had a detection limit above 20 ppm, while below this concentration the sensing response was overpowered by signal noise and some baseline drift. For a W_g/L_g=0.5 the sensor was able to detect 20 ppm H_2, but not 5 ppm, while for W_g/L_g>1 the sensors were sensitive across the entire tested range. Sensing dynamics of all structures, at 500 ppm concentration, were compared using rise (t_R) and fall (t_F) times, defined as the time required for the signal to rise/fall from 10% to 90% of the steady state (table I.). The response time (t_R) reduced with increasing W_g/L_g, while the recovery (t_F) time increased. Therefore, by optimizing the sensor geometry the response characteristics can be tuned to comply with application requirements.

TABLE I. TRANSIENT PARAMETERS OF THE STUDIED SENSOR LAYOUTS.

Ratio	**t_R (min)**	**t_F (min)**
0.25	13.7	11.55
0.5	11.95	17.45
5	7.05	21.2
10	5.7	25.65

IV. CONCLUSIONS

In this work, we have studied the effects of gate electrode geometry on the H_2 gas sensing performance of Pt-AlGaN/GaN HEMT sensors by varying W_g/L_g ratios. A significant increase in sensing sensitivity of 217 % and signal variation of 4630 % was measured with larger ratio devices. W_g/L_g ratios >1 enabled the detection of H_2 across the entire tested range (5 ppm – 500 ppm). Transient characteristics demonstrated a trade-off between response and recovery times with larger W_g/L_g leading to faster response to H_2, but a slower signal recovery to the baseline value.

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