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**DOI**

[10.1016/j.snb.2018.08.015](https://doi.org/10.1016/j.snb.2018.08.015)

**Publication date**

2018

**Document Version**

Final published version

**Published in**

Sensors and Actuators, B: Chemical

**Citation (APA)**

Sokolovskij, R., Zhang, J., Iervolino, E., Zhao, C., Santagata, F., Wang, F., Yu, H., Sarro, P. M., & Zhang, G. Q. (2018). Hydrogen sulfide detection properties of Pt-gated AlGaN/GaN HEMT-sensor. *Sensors and Actuators, B: Chemical*, 274, 636-644. <https://doi.org/10.1016/j.snb.2018.08.015>

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## Hydrogen sulfide detection properties of Pt-gated AlGaIn/GaN HEMT-sensor

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### ARTICLE INFO

#### Keywords:

AlGaIn/GaN

Pt

HEMT

H<sub>2</sub>S

Gas sensor

2DEG

### ABSTRACT

AlGaIn/GaN high electron mobility transistor (HEMT)-based sensors with catalytic platinum gate were micro-fabricated on commercially available epitaxial wafers and extensively characterized for ppm level hydrogen sulfide (H<sub>2</sub>S) detection for industrial safety applications. High operating temperature above 150 °C enabled large signal variation ( $\Delta I_{DS}$ ) of 2.17 and sensing response of 112% for 90 ppm H<sub>2</sub>S in dry air as well as high stability across a wide range of biasing conditions. Transient response measurements demonstrated stable operation, superb response and recovery, with good repeatability. The measured sensing signal rise (fall) times reduced from 476 (1316) s to 219 (507) s when the temperature was increased from 200 °C to 250 °C. The response to 90 ppm H<sub>2</sub>S was 4.5x larger than to H<sub>2</sub> and the device showed stable operation over an extended time period.

### 1. Introduction

With the continuous and rapid industrial growth, environmental pollution monitoring and assurance of worker safety raise increasing concerns. H<sub>2</sub>S is a toxic, flammable, colorless gas with characteristic pungent odor [1]. It is naturally produced from sewage, liquid manure, sulfur hot springs and biogas [2]. H<sub>2</sub>S is also a by-product of coal mining, petroleum and natural gas refinement industries [3]. Extended exposure to 10–500 ppm H<sub>2</sub>S concentrations can cause symptoms varying from rhinitis to loss of consciousness and even respiratory failure. Furthermore, continuous inhalation of concentration above 100 ppm will cause inhibition of sensing the characteristic odor, due to olfactory fatigue [2,4], which can result in false assumption of the gas being dissipated. Hence, portable, wearable and reliable detectors, capable of sensing low ppm levels of H<sub>2</sub>S are of crucial importance to ensure worker safety for the fossil fuel and other energy production industries.

The first solid state gas sensor based on silicon metal oxide semiconductor (MOS) field effect transistor (FET), using palladium (Pd) as hydrogen (H<sub>2</sub>) sensitive layer, was reported in 1975 [5]. Numerous modifications of the original transducer were further developed to enhance performance in terms of sensor sensitivity and expand the range

of detectable gases. These devices include the suspended gate FET (SG-FET) [6], hybrid SG-FET [7], capacitively controlled FET (CCFET) [8], floating gate FET (FG-FET) [9] and most recently the horizontal FG-FET [10]. However, because of the narrow energy bandgap of Si (1.12 eV), these GasFETs are not able of operating at temperatures above 200 °C. In fact, initial reports on silicon Pd-MOS H<sub>2</sub>S sensors have demonstrated operation at temperature up to 150 °C [11,12]. To overcome the limitations related to the use of Si, wider bandgap 2<sup>nd</sup> generation compound III-V semiconductors, including InP [13], GaAs [14,15], InGaP [16], InAlAs [17], have been previously investigated for gas sensing applications. While these devices achieved improved sensing performance, the requirement of costly and fragile GaAs or InP substrates for layer epitaxy limits their large-scale adoption. 3<sup>rd</sup> generation wide bandgap (> 3 eV) silicon carbide (SiC) and gallium nitride (GaN) materials are favorable for development of high performance gas sensors. The price of SiC substrates is currently very high, while GaN can be grown on cost effective sapphire or Si wafers. Hence gallium nitride, with a bandgap of 3.4 eV, is particularly advantageous for harsh environment, high temperature electronics and sensor applications [18]. AlGaIn/GaN heterostructure Schottky diode and high electron mobility transistor (HEMT) based H<sub>2</sub> sensors have been demonstrated operating at 800 °C under N<sub>2</sub> ambient [19,20]. While most studies refer to H<sub>2</sub>

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<https://doi.org/10.1016/j.snb.2018.08.015>

Received 14 January 2018; Received in revised form 3 August 2018; Accepted 4 August 2018

Available online 06 August 2018

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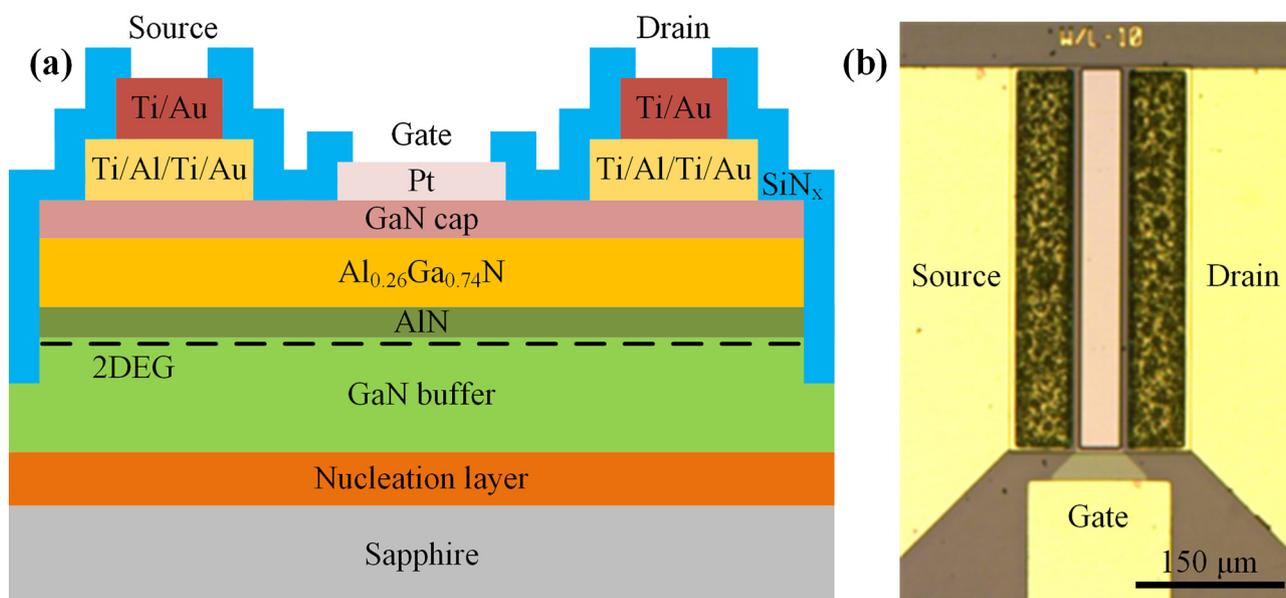


Fig. 1. (a) Schematic cross-section of the studied Pt-AlGaIn/GaN HEMT H<sub>2</sub>S sensor. (b) Top view optical micrograph of the fabricated sensor.

sensors [21–23], AlGaIn/GaN sensors were also demonstrated for CO, CO<sub>2</sub>, NO, NO<sub>2</sub>, NH<sub>3</sub>, Cl, CH<sub>4</sub>, C<sub>2</sub>H<sub>2</sub> [24–30]. Very few results of H<sub>2</sub>S detection with wide bandgap semiconductor devices have been reported so far. A GaN Schottky diode with Pt gas sensing layer has been demonstrated for 0.1 ~ 10 ppm H<sub>2</sub>S detection under N<sub>2</sub> ambient [31]. A Silicon carbide FET with Pt and Ir gates was also shown to sense H<sub>2</sub>S, however signal saturation was observed at low concentration of 6 ~ 8 ppm under 5% oxygen atmosphere [32]. Recently we presented successful sensing of H<sub>2</sub>S with Pt-AlGaIn/GaN HEMT based sensor [33]. In this work, we further expand on our preliminary results by comprehensively studying DC and transient characteristics at different temperatures and H<sub>2</sub>S concentrations in dry air atmosphere. Moreover, the measured signal variations and sensing responses at different bias points are evaluated and sensor stability, selectivity and repeatability are demonstrated.

## 2. Experimental

### 2.1. Fabrication of sensors

The epitaxial structure used for device fabrication was purchased from a commercial vendor, Suzhou Nanowin Co. The material was grown by MOCVD on 2 inch C-plane sapphire wafers. Starting from the substrate, the stack consisted of a proprietary nucleation layer, for lattice mismatch compensation, a 1.8 μm GaN buffer, 1 nm AlN interlayer, followed by an undoped 21 nm Al<sub>0.26</sub>Ga<sub>0.74</sub>N barrier and 1 nm GaN capping layer. The basis for HEMT operation is the formation of a high electron density channel, two-dimensional electron gas (2DEG), at the AlGaIn/GaN heterojunction interface, due to polarization effects [34].

The sensor fabrication started with wet chemical cleaning of the substrate using acetone, isopropanol and DI water rinsing. Afterwards 100 nm deep mesa etching was performed by ICP BCl<sub>3</sub>/Cl<sub>2</sub> plasma to isolate individual devices. Then ohmic contacts consisting of a Ti/Al/Ti/Au stack with thickness of 20/110/40/50 nm, were e-beam evaporated and patterned by lift-off. A 60 s dip in HCl:H<sub>2</sub>O solution was done right before loading the wafers into the

deposition chamber to remove any surface oxide [35]. After patterning, the contacts were annealed for 47 s at 870 °C in N<sub>2</sub> ambient. The gas sensing gate electrode was then formed by e-beam evaporation and lift-off of a 10 nm Pt layer. Then a bi-layer of 30/300 nm Ti/Au interconnect metal was evaporated and patterned by lift-off to guarantee reliable wire bonding. Finally, the devices were passivated by a 500 nm PECVD SiN<sub>x</sub> layer followed by combined RIE and wet BOE etching to open the sensing area and the bonding pads. The schematic cross-section and top view optical micrograph of the fabricated device are shown in Fig. 1. The gate dimensions exposed to gas were 40 μm × 400 μm and the gate-source and gate-drain spacing was 6 μm, based on our earlier report [36]. After fabrication, the wafers were diced and individual devices were wire bonded to ceramic substrates for high temperature measurements.

### 2.2. Testing of sensors

Gas testing was performed using a commercial gas mixing system from Beijing Elite Tech Co., which consists of mass flow controllers (MFC) to dilute the calibration gas, a 1.8 L volume chamber with temperature controlled hotplate, temperature and humidity sensors and electrical feedthroughs. The sensors were tested at different temperatures using H<sub>2</sub>S reference gas diluted with dry synthetic air (O<sub>2</sub>/N<sub>2</sub> = 21%/79%) to ensure 0% relative humidity. The combined total gas flow was kept at 310 sccm. Electrical sensor measurements were conducted using a pair of Keithley 2450 source meters. Prior to gas sensing experiments the sensors underwent a burn-in procedure in dry air ambient for 24 h at 150 °C with gate and drain bias voltages of 0 V and 5 V respectively in order to minimize baseline drift. Afterwards sensor activation was carried out with H<sub>2</sub> pulses of increasing concentration from 100 to 900 ppm with air purges in-between at 250 °C. We observed that such treatment allowed to extend the upper limit of H<sub>2</sub>S detection before signal saturation occurred. Exposure to H<sub>2</sub> can reform the surface morphology of Pt [37] and increase the number of surface sites for gas adsorption. Further investigations into the mechanism of H<sub>2</sub> based activation are currently ongoing.

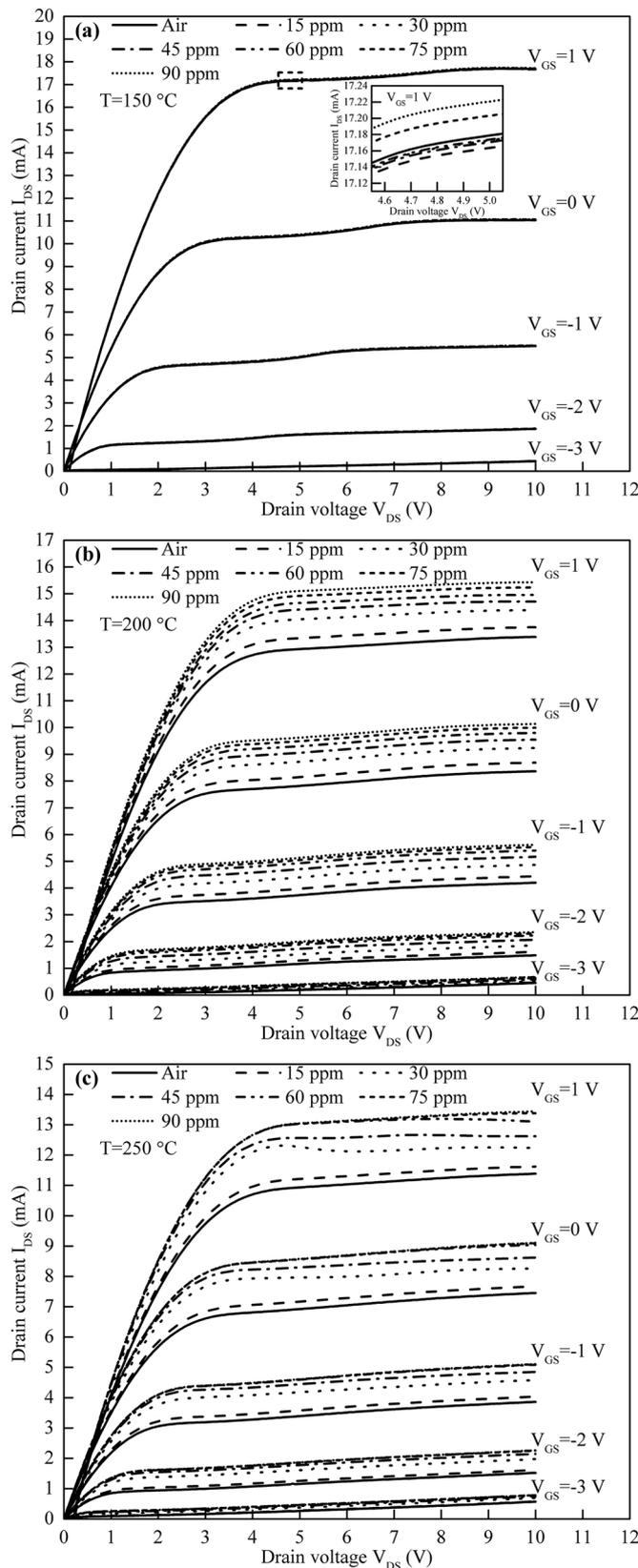


Fig. 2. Output ( $I_{DS}$ - $V_{DS}$ ) characteristics of Pt-HEMT sensors exposed to different  $H_2S$  concentrations at (a)  $150^\circ\text{C}$ , with the inset showing a magnified view of the box area, (b)  $200^\circ\text{C}$  and (c)  $250^\circ\text{C}$ .

### 3. Results and discussion

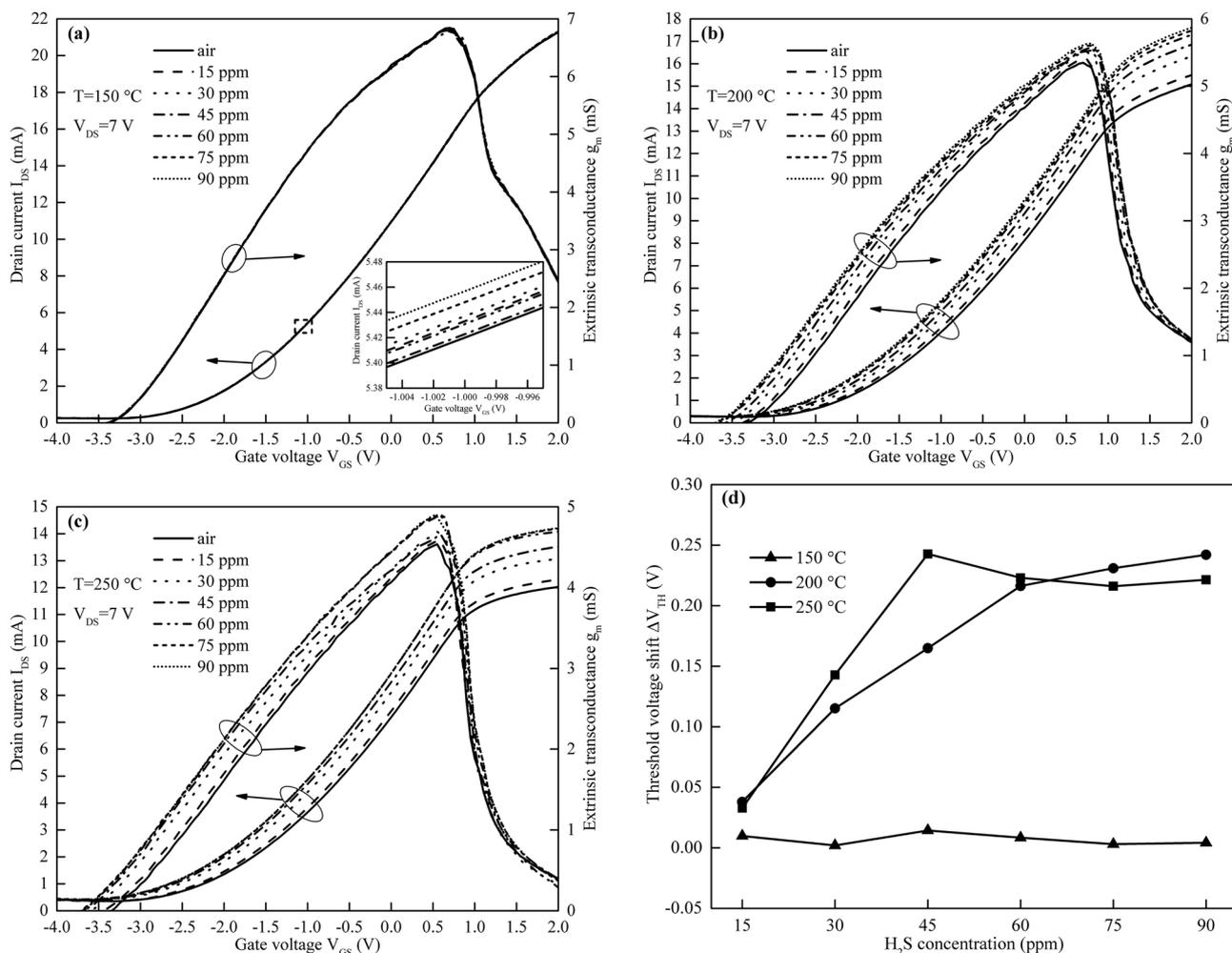
The steady state sensing characteristics of the Pt-HEMT sensor were studied by measuring the drain current versus drain-source voltage ( $I_{DS}$ - $V_{DS}$ ) and the drain current versus gate-source voltage ( $I_{DS}$ - $V_{GS}$ ). Output ( $I_{DS}$ - $V_{DS}$ ) characteristics upon exposure to  $H_2S$ /Air concentrations of 15–90 ppm at temperatures of  $150^\circ\text{C}$ ,  $200^\circ\text{C}$  and  $250^\circ\text{C}$  are shown in Fig. 2(a–c). The gate-source voltage ( $V_{GS}$ ) was stepped from  $-3\text{ V}$  to  $1\text{ V}$  with  $1\text{ V}$  increments. Proper transistor operation is clearly observed with distinct linear and saturation regions and the ability to modulate output current via the gate terminal is maintained at all tested temperatures. A profound rise in drain current was observed at  $200^\circ\text{C}$  and  $250^\circ\text{C}$  with increasing  $H_2S$  concentrations. At  $250^\circ\text{C}$  the sensing signal started to saturate at concentrations above 60 ppm/air. The magnitude of current variation at  $150^\circ\text{C}$  was much lower, with noticeable instability below 75 ppm/air. The corresponding transfer ( $I_{DS}$ - $V_{GS}$ ) and transconductance ( $g_m$ ) characteristics at  $V_{DS} = 7\text{ V}$  are shown in Fig. 3(a–c). Upon exposure to  $H_2S$  the curves shift towards more negative voltages for the same  $I_{DS}$  levels. The maximum transconductance ( $g_{m,max}$ ) values increased from 6.82, 5.35, 4.54 mS in air ambient to 6.83, 5.63, 4.89 mS when exposed to 90 ppm/air at temperatures of  $150^\circ\text{C}$ ,  $200^\circ\text{C}$  and  $250^\circ\text{C}$  respectively. Higher transconductance in  $H_2S$  containing ambient is attributed to increased number of electrons in the 2DEG channel due to gas interaction with the Pt gate which is also evident from Fig. 2. Threshold voltage ( $V_{TH}$ ) values at tested concentrations were extracted from Fig. 3(a–c) using the linear extrapolation method by fitting a tangent line at the point of  $g_{m,max}$  to the  $V_{GS}$  axis intercept [38]. The threshold voltage shift, defined as  $\Delta V_{TH} = V_{TH,air} - V_{TH,H_2S}$ , for the tested  $H_2S$  concentration range is shown in Fig. 3(d). Clearly the magnitude of  $\Delta V_{TH}$  increases with increasing test gas concentration at  $200^\circ\text{C}$  and  $250^\circ\text{C}$ . At  $150^\circ\text{C}$   $\Delta V_{TH}$  mostly unchanged, due to low catalytic dissociation efficiency of  $H_2S$  on Pt at this temperature. Output and transfer characteristics before and after exposure to 90 ppm  $H_2S$ /Air are shown in Fig. 4(a) and (b) respectively. After the initial baseline measurements in dry air at  $250^\circ\text{C}$ ,  $H_2S$  was injected into the test chamber for 20 min followed by an air purge for 60 min. From Fig. 4(a) an increase of 0.26 mA was observed for the baseline current (at  $V_{GS} = 0\text{ V}$ ,  $V_{DS} = 5\text{ V}$ ) and a corresponding  $-0.06\text{ V}$  shift (Fig. 4(b)) of the transfer curve (at  $I_{DS} = 5\text{ mA}$ ). It was observed that after the sensor was exposed to ambient conditions for several hours the baseline values were restored. To understand the current and threshold voltage variations and analyze the gas sensing mechanism we first look at the saturation drain current of an AlGaIn/GaN HEMT expressed as:

$$I_{DS,sat} = \frac{\mu C_b W_g}{2L_g} (V_{GS} - V_{TH})^2 \quad (1)$$

where  $\mu$  is the 2DEG mobility,  $W_g/L_g$  the gate width/length,  $C_b$  is gate to channel capacitance, which is the sum of capacitance contributions from each layer between the gate metal and 2DEG ( $1/C_b = 1/C_{cap} + 1/C_{AlGaIn} + 1/C_{AIN} + 1/C_{2DEG}$ ). The  $\mu$  and  $C_b$  are determined by the quality and structure of the epitaxy, while  $W_g/L_g$  are defined by sensor design. The shift in threshold voltage towards more negative value would result in the observed  $I_{DS}$  increase in  $H_2S$  containing atmosphere. The expression of  $V_{TH}$  for an AlGaIn/GaN HEMT is:

$$V_{TH} = \Phi_b - \frac{\Delta E_C}{q} - \frac{qn_s}{C_b} \quad (2)$$

where  $\Phi_b$  is the Schottky barrier height,  $\Delta E_C$  is the conduction band discontinuity,  $q$  is the elementary charge and  $n_s$  is the sheet charge carrier density. The Schottky barrier height is in turn dependent on the



**Fig. 3.** Transfer ( $I_{DS}$ - $V_{GS}$ ) and transconductance characteristics of Pt-HEMT sensors exposed to different  $H_2S$  concentrations at (a) 150 °C, with the inset showing a magnified view of the box area, (b) 200 °C and (c) 250 °C. (d) Threshold voltage shift versus  $H_2S$  concentration.

work function ( $\Phi_m$ ) of the gate metal and the semiconductor electron affinity ( $\chi_s$ ),  $\Phi_b = \Phi_m - \chi_s$ . Previous research has found that hydrogen containing gas molecules upon adsorption on the surface of catalytic metals (e.g. Pt, Pd or Ir) dissociate and release hydrogen atoms [21,27,29]. In the case of  $H_2S$  adsorption in air ambient the probable reaction mechanism is as follows [39]:

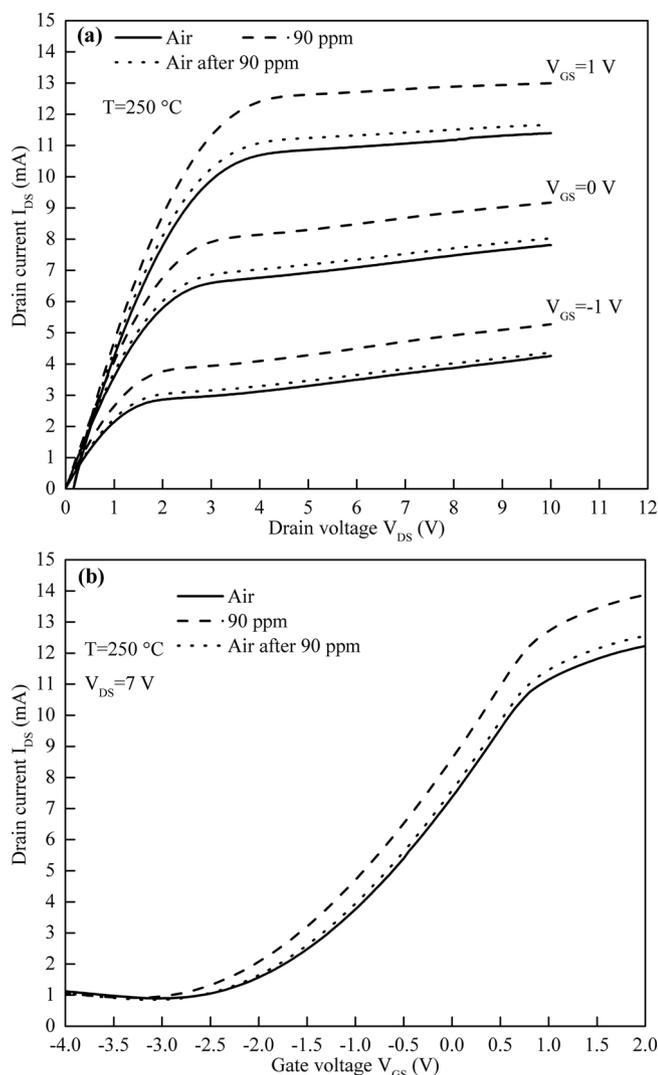


The S–H bonds are broken sequentially as described by (3) and (4) and the remaining sulfur reacts with  $O_2$  present at the Pt surface and forms  $SO_2$  which can then desorb from the surface. The hydrogen ions rapidly diffuse through the Pt to the M–S interface. It is assumed that there is an interfacial oxide layer present on the GaN surface, since it was exposed to ambient conditions during sensor fabrication for several hours and no chemical or plasma treatments were performed prior to Pt deposition. The oxide layer supplies bonding sites for the diffused H resulting in a dipole layer at the interface [40]. This causes the reduction of metal work function ( $\Phi_m$ ) and the lowering of the  $\Phi_b$ , which results in the observed  $\Delta V_{TH}$  and  $I_{DS}$  increase in  $H_2S$  containing

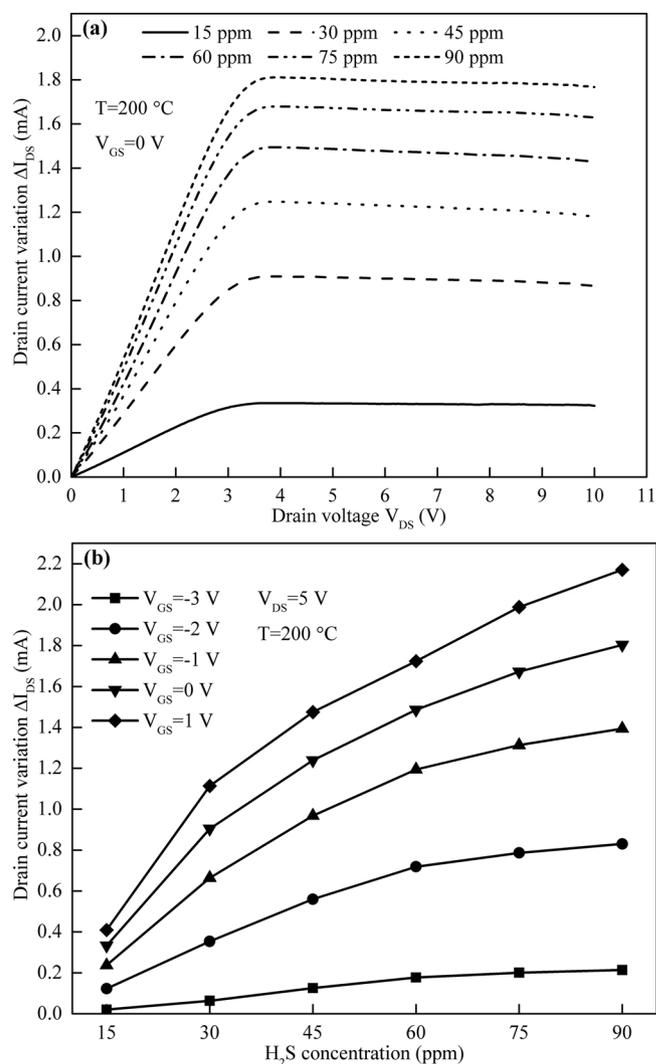
atmosphere. To evaluate the hydrogen sulfide detection performance of our Pt-HEMT sensor, we calculated the sensing response defined as:

$$S(\%) = \frac{\Delta I_{DS}}{I_{DS,air}} \times 100\% \tag{6}$$

where  $\Delta I_{DS} = I_{DS,H_2S} - I_{DS,air}$  is the drain current variation between  $H_2S$  and air ambient. Fig. 5(a) shows the  $\Delta I_{DS}$  as a function of drain-source voltage ( $V_{DS}$ ) for  $V_{GS} = 0$  V at temperature of 200 °C. Measurements indicated that the  $\Delta I_{DS}$  increases linearly with  $V_{DS}$  in the transistor linear region until it reaches the maximum value at the transition point to the saturation region at approximately 4 V, and then reduces by only 4% at  $V_{DS} = 10$  V. This demonstrates that our sensor exhibits high stability and allows for a wide selection of biasing conditions without diminishing sensing performance. The drain current variation at different  $H_2S$  concentrations and gate bias voltages is shown in Fig. 5(b). The magnitude of sensing signal variation is greatly impacted by the gate bias. For 90 ppm  $H_2S$  concentration the measured  $\Delta I_{DS}$  increased tenfold, from 0.21 mA at  $V_{GS} = -3$  V to 2.17 mA at  $V_{GS} = 1$  V. The  $\Delta I_{DS}$  increase is due to larger baseline current ( $I_{DS,air}$ ) with increasing gate bias. Fig. 6(a) shows the hydrogen sulfide sensing response at different gate bias voltages, while Fig. 6(b) shows response at different temperatures. Looking at Eq. (6) the reduction of  $S$  is due to larger increase of  $I_{DS,air}$



**Fig. 4.** (a) Output ( $I_{DS}$ - $V_{DS}$ ) and (b) transfer ( $I_{DS}$ - $V_{GS}$ ) characteristics of the Pt-HEMT sensor before and after exposure to 90 ppm of  $\text{H}_2\text{S}$  at  $250\text{ }^\circ\text{C}$ .



**Fig. 5.** (a) Drain current variation ( $\Delta I_{DS}$ ) as a function of drain-source ( $V_{DS}$ ) voltage for different  $\text{H}_2\text{S}$  concentrations at  $200\text{ }^\circ\text{C}$ ,  $V_{GS} = 0\text{ V}$ . (b) Drain current variation ( $\Delta I_{DS}$ ) versus  $\text{H}_2\text{S}$  concentration at  $200\text{ }^\circ\text{C}$ ,  $V_{DS} = 5\text{ V}$ .

with higher  $V_{GS}$  than the increase in  $\Delta I_{DS}$ . Based on Fig. 5(b) we conclude that HEMT type sensor can be operated at high signal amplitude ( $\Delta I_{DS}$ ) conditions ( $V_{GS} > 0\text{ V}$ ) to achieve the lowest gas detection limits. Alternatively, as shown in Fig. 6(a), operating in high response mode is possible when gate bias is approaching pinch-off state thereby minimizing sensor power consumption. GaN Schottky diode type  $\text{H}_2$  sensor had been previously demonstrated with very high response of  $\sim 3500\%$  at  $150\text{ }^\circ\text{C}$ , however the signal amplitude was on the order of nA [41]. From Fig. 6(b) it is evident that response towards  $\text{H}_2\text{S}$  increased with higher temperature, however saturation started to occur earlier, namely above 60 ppm concentration.

Fig. 7 shows transient characteristics of the Pt-HEMT sensors at the tested temperatures and increasing analyte gas concentrations. The bias conditions used were  $V_{DS} = 5\text{ V}$ ,  $V_{GS} = 0\text{ V}$  to obtain high  $\Delta I_{DS}$  and operate the sensor as 2-terminal device with gate and source terminals shorted. The drain current increased immediately upon injecting  $\text{H}_2\text{S}$ , with the operating temperature having a significant impact on the observed response. At  $150\text{ }^\circ\text{C}$  there is substantial

baseline value drift at 15 ppm and 30 ppm, followed by minimal signal variation with increasing concentration. It is believed to be caused by sulfur poisoning of the Pt surface due to incomplete oxidation to  $\text{SO}_2$  and desorption at this temperature [12]. Raising the temperature to  $200\text{ }^\circ\text{C}$  resulted in an increased signal and improved recovery of the sensor, while at  $250\text{ }^\circ\text{C}$  the sensor rapidly reached steady state after gas introduction and returned to the baseline level during air purge steps. Moreover signal saturation was less profound compared with DC measurements. The increased magnitude of response current at  $200\text{ }^\circ\text{C}$  and  $250\text{ }^\circ\text{C}$  is due to enhanced reaction rate of H-S bond cleavage and H atom diffusion through the Pt gate. The baseline current value in air ambient reduces with rising temperature due to reduction of electron mobility in 2DEG channel.

Response and recovery rates were estimated 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 values. This method was used to reduce the influence of the delay necessary to equilibrate gas concentration inside the testing chamber. Fig. 8(a) and (b) shows the  $t_R$  and  $t_F$  as function of  $\text{H}_2\text{S}$  concentration at tested temperatures. The transient

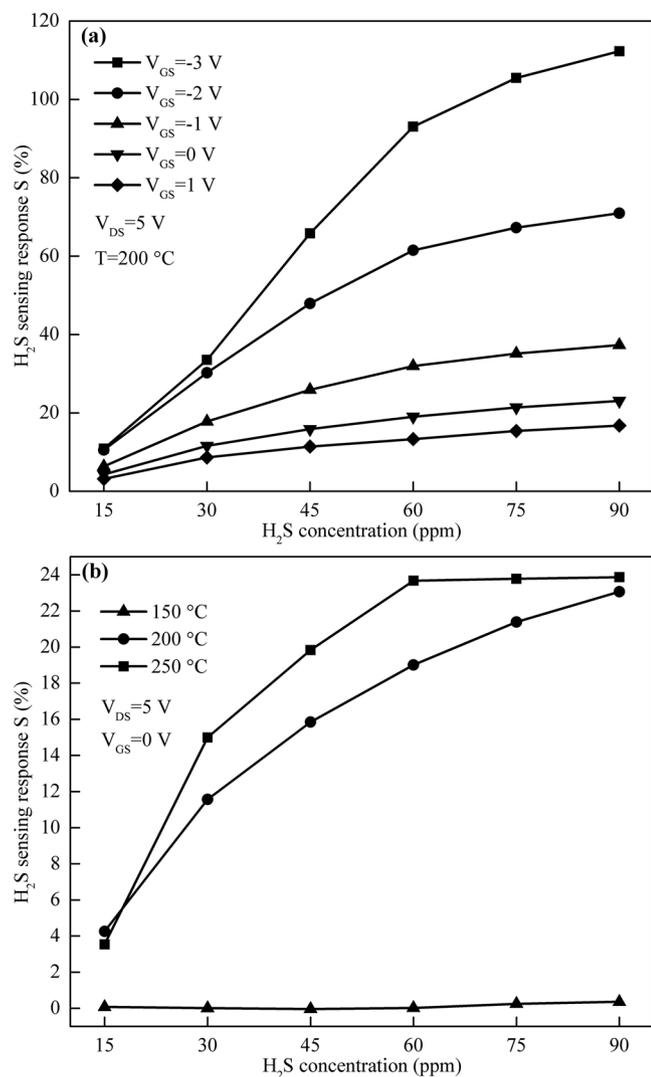


Fig. 6. Hydrogen sulfide sensor sensitivity at (a) various gate bias voltages and (b) at different temperatures.

times decreased with increasing gas concentration for 200 °C and 250 °C. The results at 150 °C were irregular due to low signal variation and baseline current value drift at 15 ppm and 30 ppm gas concentrations which resulted in quicker  $t_R$  and  $t_F$ . Starting with 45 ppm the baseline stabilized and the response (recovery) times became more consistent. At 90 ppm H<sub>2</sub>S concentration  $t_R$  ( $t_F$ ) reduced from 476 (1316) s at 200 °C to 219 (507) s at 250 °C. The shorter rise/fall times are attributed to faster gas adsorption and desorption kinetics at the Pt surface and M–S interface with increasing temperature. Further decrease of  $t_R$  and  $t_F$  is expected with downsizing the volume of the testing chamber. Fig. 9 shows 5 consecutive exposure and purge cycles of 90 ppm H<sub>2</sub>S. Obviously the sensor demonstrates repeatable and reversible current variation characteristics under continuous operation at 250 °C.

Pd and Pt gate field effect devices are known to detect H<sub>2</sub> gas, therefore a comparison of response between H<sub>2</sub>S and H<sub>2</sub> was carried out. Fig. 9(a) shows the transient drain current curves of the tested sensor exposed to 60 ppm and 90 ppm of H<sub>2</sub>S, H<sub>2</sub> and NO<sub>2</sub> at 250 °C. The sensing response to 90 ppm for each gas is summarized in Fig. 9(b). It is evident that the response to H<sub>2</sub>S was 4.5x higher than to H<sub>2</sub>, while the response to NO<sub>2</sub> was negligible and I<sub>DS</sub> decreased upon gas exposure (Fig. 10).

Long-term operation stability of the Pt-HEMT sensor was tested by performing the H<sub>2</sub>S tests over a period of 15 days. Fig. 11 shows the daily drain current variation ( $\Delta I_{DS}$ ) for 60 ppm and 90 ppm H<sub>2</sub>S at

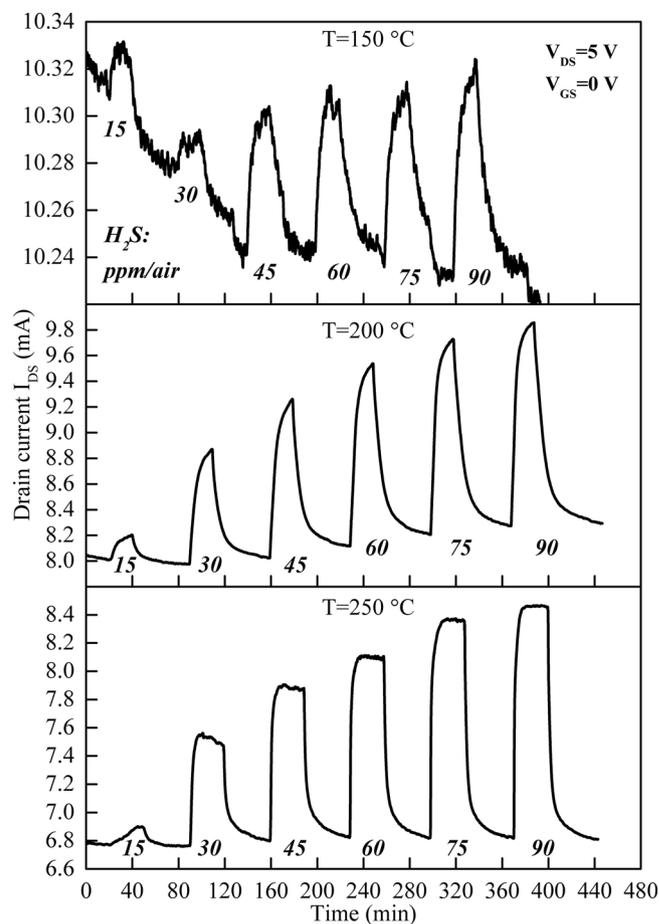


Fig. 7. Transient response characteristics upon injection and purge of H<sub>2</sub>S in dry air ambient at 150 °C, 200 °C and 250 °C (from top to bottom). During all measurements V<sub>DS</sub> = 5 V, V<sub>GS</sub> = 0 V.

250 °C. There was no significant deterioration of the sensing signal during the testing period. We did observe however that the Au-plated pads of our ceramic testing substrates and bond-pads of the HEMT chip were corroded after extended exposure to H<sub>2</sub>S, therefore packaging reliability needs to be further investigated to ensure stable sensor operation.

#### 4. Conclusions

Sensors based on AlGaIn/GaN HEMTs with Pt catalytic gate were fabricated and characterized for detecting ppm levels of hydrogen sulfide at high temperature. The developed devices exhibited a significant drain current increase and threshold voltage shift upon exposure to the test gas. At 200 °C maximum  $\Delta I_{DS}$  of 2.17 mA (V<sub>GS</sub> = 1 V) as well as high sensing response of 112% (V<sub>GS</sub> = -3 V) for 90 ppm H<sub>2</sub>S was obtained. High stability was observed with only 4% reduction of  $\Delta I_{DS}$  across the tested drain saturation voltage range, which enables a wide selection of biasing conditions. At 150 °C very low response and baseline drift were likely caused by sulfur poisoning effect of the Pt gate. Transient measurements confirmed stable operation with excellent response, recovery and repeatability properties. The rise (fall) times reduced from 476 (1316) s to 219 (507) s when the temperature was elevated from 200 °C to 250 °C. Sensing response of H<sub>2</sub>S was 4.5x greater than H<sub>2</sub> for 90 ppm concentration. The operating stability was validated over 15 days with no significant reduction of sensing signal. Our findings firmly suggest that AlGaIn/GaN HEMT sensors are a promising technology for industrial wearable worker safety detectors.

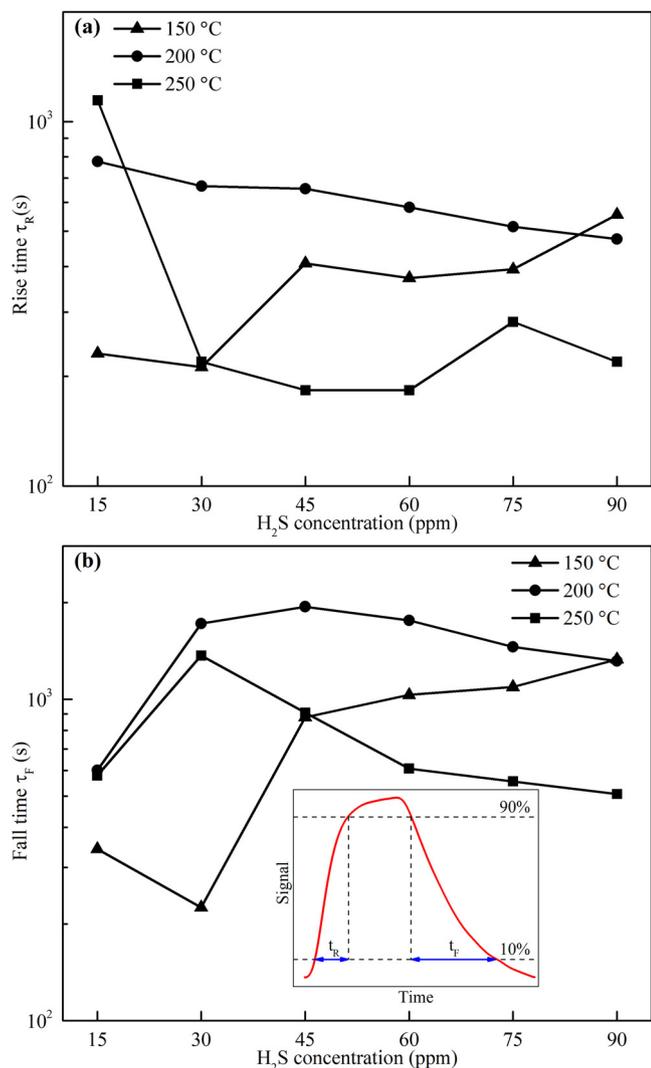


Fig. 8. (a) Rise time ( $t_R$ ) and (b) fall time ( $t_F$ ) versus H<sub>2</sub>S concentration at 150 °C, 200 °C and 250 °C. The inset schematically shows the definition of  $t_R$  and  $t_F$ .

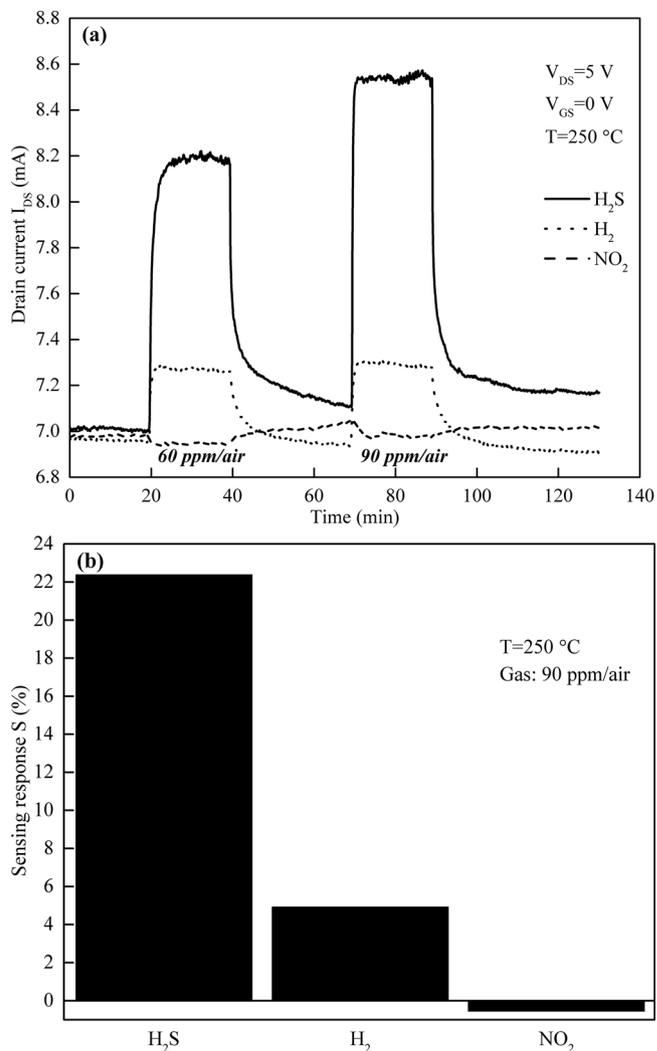


Fig. 10. (a) Transient response characteristics upon exposure to 60 ppm and 90 ppm of H<sub>2</sub>S, H<sub>2</sub> and NO<sub>2</sub> at 250 °C in dry air ambient. (b) Sensing response towards 90 ppm of H<sub>2</sub>S, H<sub>2</sub> and NO<sub>2</sub>.

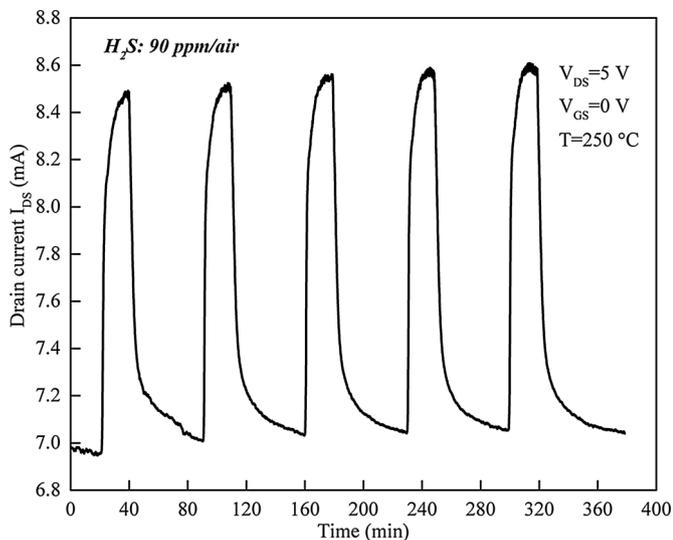


Fig. 9. Five repetitive cycles of sensor exposure to 90 ppm of H<sub>2</sub>S at 250 °C.

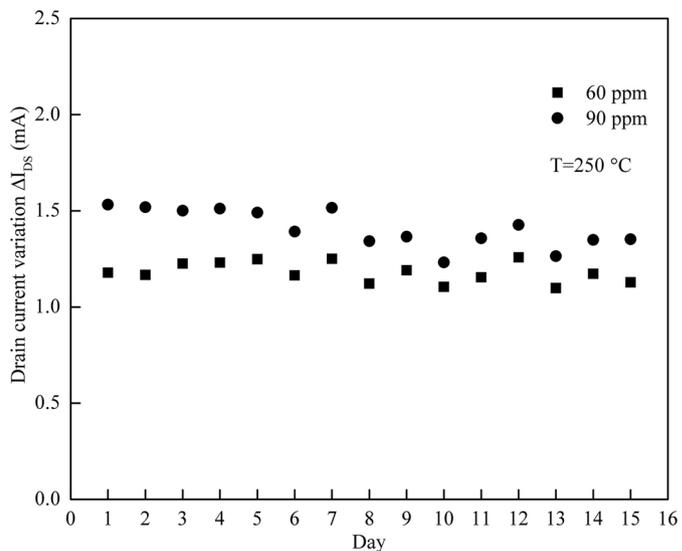


Fig. 11. Sensor drain current variation ( $\Delta I_{DS}$ ) characteristics towards 60 and 90 ppm of H<sub>2</sub>S over 15 day testing period at 250 °C.

## Acknowledgments

The authors would like to thank Prof. Junxi Wang and the staff of Institute of Semiconductors, Chinese Academy of Sciences for their assistance in device fabrication. This research was funded by State Key Laboratory of Solid State Lighting, Changzhou base and “Research of low cost fabrication of GaN power devices and system integration” research fund (Grant no: JCYJ201602226192639004), “Research of AlGaIn HEMT MEMS sensor for work in extreme environment” (Grant no: JCYJ20170412153356899) and “Research of the reliability mechanism and circuit simulation of GaN HEMT” (Grant No: 2017A050506002).

## References

- [1] H.-M. Huang, H.-Y. Li, X.-X. Wang, X. Guo, Detecting low concentration of H<sub>2</sub>S gas by BaTiO<sub>3</sub> nanoparticle-based sensors, *Sens. Actuators B* 238 (2017) 16–23, <https://doi.org/10.1016/j.snb.2016.06.172>.
- [2] E.-C. Lee, J. Kwan, J.-H. Leem, S.-G. Park, H.-C. Kim, D.-H. Lee, J.-H. Kim, D.-H. Kim, Hydrogen sulfide intoxication with dilated cardiomyopathy, *J. Occup. Health* 51 (2009) 522–525, <https://doi.org/10.1539/joh.N9004>.
- [3] F. Zhang, A. Zhu, Y. Luo, Y. Tian, J. Yang, Y. Qin, CuO nanosheets for sensitive and selective determination of H<sub>2</sub>S with high recovery ability, *J. Phys. Chem. C* 114 (2010) 19214–19219, <https://doi.org/10.1021/jp106098z>.
- [4] B. Doujjaji, J.A. Al-Tawfiq, Hydrogen sulfide exposure in an adult male, *Ann. Saudi Med.* 30 (2010) 76–80, <https://doi.org/10.4103/0256-4947.59379>.
- [5] K.I. Lundström, M.S. Shivaraman, C.M. Svensson, A hydrogen-sensitive Pd-gate MOS transistor, *J. Appl. Phys.* 46 (1975) 3876–3881, <https://doi.org/10.1063/1.322185>.
- [6] H. Lorenz, M. Peschke, H. Riess, J. Janata, I. Eisele, New suspended gate FET technology for physical deposition of chemically sensitive layers, *Sens. Actuators A* 23 (1990) 1023–1026, [https://doi.org/10.1016/0924-4247\(90\)87082-T](https://doi.org/10.1016/0924-4247(90)87082-T).
- [7] I. Eisele, T. Doll, M. Burgmair, Low power gas detection with FET sensors, *Sens. Actuators B* 78 (2001) 19–25, [https://doi.org/10.1016/S0925-4005\(01\)00786-9](https://doi.org/10.1016/S0925-4005(01)00786-9).
- [8] Z. Gergintschew, P. Kornetzky, D. Schipanski, The capacitively controlled field effect transistor (CCFET) as a new low power gas sensor, *Sens. Actuators B* 36 (1996) 285–289, [https://doi.org/10.1016/S0925-4005\(97\)80083-4](https://doi.org/10.1016/S0925-4005(97)80083-4).
- [9] M. Burgmair, H.P. Frerichs, M. Zimmer, M. Lehmann, I. Eisele, Field effect transducers for work function gas measurements: device improvements and comparison of performance, *Sens. Actuators B* 95 (2003) 183–188, [https://doi.org/10.1016/S0925-4005\(03\)00412-X](https://doi.org/10.1016/S0925-4005(03)00412-X).
- [10] C.H. Kim, I.T. Cho, J.M. Shin, K.B. Choi, J.K. Lee, J.H. Lee, A new gas sensor based on MOSFET having a horizontal floating-gate, *IEEE Electron Device Lett.* 35 (2014) 265–267, <https://doi.org/10.1109/LED.2013.2294722>.
- [11] M.S. Shivaraman, Detection of H<sub>2</sub>S with Pd-gate MOS field-effect transistors, *J. Appl. Phys.* 47 (1976) 3592–3593, <https://doi.org/10.1063/1.323162>.
- [12] Z. Weixin, Z. Yibing, The temperature characteristics of an H<sub>2</sub>S-sensitive Pd-gate MOS transistor, *Sens. Actuators* 15 (1988) 85–93, [https://doi.org/10.1016/0250-6874\(88\)85020-0](https://doi.org/10.1016/0250-6874(88)85020-0).
- [13] L. Wen-Chau, P. Hsi-Jen, C. Huey-Ing, L. Kun-Wei, C. Shiou-Ying, Y. Kuo-Hui, Hydrogen-sensitive characteristics of a novel Pd/InP MOS Schottky diode hydrogen sensor, *IEEE Trans. Electron Devices* 48 (2001) 1938–1944, <https://doi.org/10.1109/16.944180>.
- [14] M. Jaegle, K. Steiner, Gas-sensitive GaAs-MESFETs, *Sens. Actuators B* 34 (1996) 543–547, [https://doi.org/10.1016/S0925-4005\(96\)01859-X](https://doi.org/10.1016/S0925-4005(96)01859-X).
- [15] C.-W. Hung, K.-W. Lin, R.-C. Liu, Y.-Y. Tsai, P.-H. Lai, S.-I. Fu, T.-P. Chen, H.-I. Chen, W.-C. Liu, On the hydrogen sensing properties of a Pd/GaAs transistor-type gas sensor in a nitrogen ambient, *Sens. Actuators B* 125 (2007) 22–29, <https://doi.org/10.1016/j.snb.2007.01.027>.
- [16] C.-C. Cheng, Y.-Y. Tsai, K.-W. Lin, H.-I. Chen, W.-H. Hsu, C.-W. Hong, W.-C. Liu, Characteristics of a Pd-oxide-In<sub>0.49</sub>Ga<sub>0.51</sub>P high electron mobility transistor (HEMT)-based hydrogen sensor, *Sens. Actuators B* 113 (2006) 29–35, <https://doi.org/10.1016/j.snb.2005.02.019>.
- [17] T.-H. Tsai, H.-I. Chen, K.-W. Lin, Y.-W. Kuo, P.-S. Chiu, C.-F. Chang, L.-Y. Chen, T.-P. Chen, Y.-J. Liu, W.-C. Liu, On a Pd/InAlAs metamorphic high electron mobility transistor (MHEMT)-based hydrogen sensor, *Sens. Actuators B* 139 (2009) 310–316, <https://doi.org/10.1016/j.snb.2009.03.042>.
- [18] A.J. Suria, A.S. Yalamathy, H. So, D.G. Senesky, DC characteristics of ALD-grown Al<sub>2</sub>O<sub>3</sub>/AlGaIn/GaN MIS-HEMTs and HEMTs at 600 °C in air, *Semicond. Sci. Technol.* 31 (2016) 115017, <https://doi.org/10.1088/0268-1242/31/11/115017>.
- [19] J. Song, W. Lu, J.S. Flynn, G.R. Brandes, Pt-AlGaIn/GaN Schottky diodes operated at 800 °C for hydrogen sensing, *Appl. Phys. Lett.* 87 (2005) 133501, <https://doi.org/10.1063/1.2058227>.
- [20] J. Song, W. Lu, Operation of Pt/AlGaIn/GaN-Heterojunction field-effect-Transistor hydrogen sensors with low detection limit and high sensitivity, *IEEE Electron Device Lett.* 29 (2008) 1193–1195, <https://doi.org/10.1109/LED.2008.2005432>.
- [21] C.S. Hsu, H.I. Chen, P.C. Chou, J.K. Liou, C.C. Chen, C.F. Chang, W.C. Liu, Hydrogen-sensing properties of a Pd/AlGaIn/GaN-Based field-effect transistor under a nitrogen ambient, *IEEE Sensors J.* 13 (2013) 1787–1793, <https://doi.org/10.1109/JSEN.2013.2243430>.
- [22] H.-I. Chen, K.-C. Chuang, C.-H. Chang, W.-C. Chen, I.P. Liu, W.-C. Liu, Hydrogen sensing characteristics of a Pd/AlGaIn/GaN-based Schottky diode, *Sens. Actuators B* 246 (2017) 408–414, <https://doi.org/10.1016/j.snb.2017.02.085>.
- [23] Y. Xi, L. Liu, Y.-H. Hwang, O. Phillips, F. Ren, S.J. Pearton, J. Kim, C.-H. Hsu, C.-F. Lo, J. Wayne Johnson, Study of hydrogen detection response time with Pt-gated diodes fabricated on AlGaIn/GaN heterostructure, *J. Vac. Sci. Technol. B* 31 (2013) 032202, <https://doi.org/10.1116/1.4798612>.
- [24] C.-F. Lo, Y. Xi, L. Liu, S.J. Pearton, S. Doré, C.-H. Hsu, A.M. Dabiran, P.P. Chow, F. Ren, Effect of temperature on CO sensing response in air ambient by using ZnO nanorod-gated AlGaIn/GaN high electron mobility transistors, *Sens. Actuators B* 176 (2013) 708–712, <https://doi.org/10.1016/j.snb.2012.10.051>.
- [25] C.Y. Chang, B.S. Kang, H.T. Wang, F. Ren, Y.L. Wang, S.J. Pearton, D.M. Dennis, J.W. Johnson, P. Rajagopal, J.C. Roberts, E.L. Piner, K.J. Linthicum, CO<sub>2</sub> detection using polyethylenimine/starch functionalized AlGaIn/GaN high electron mobility transistors, *Appl. Phys. Lett.* 92 (2008) 232102, <https://doi.org/10.1063/1.2937126>.
- [26] Y. Halfaya, C. Bishop, A. Soltani, S. Sundaram, V. Aubry, P. Voss, J.-P. Salvestrini, A. Ougazzaden, Investigation of the Performance of HEMT-Based NO, NO<sub>2</sub> and NH<sub>3</sub> Exhaust Gas Sensors for Automotive Antipollution Systems, *Sensors* 16 (273) (2016), <https://doi.org/10.3390/s16030273>.
- [27] C. Tai-You, C. Huey-Ing, H. Chi-Shiang, H. Chien-Chang, C. Chung-Fu, C. Po-Cheng, L. Wen-Chau, On an Ammonia gas sensor based on a Pt/AlGaIn heterostructure field-effect transistor, *IEEE Electron Device Lett.* 33 (2012) 612–614, <https://doi.org/10.1109/LED.2012.2184832>.
- [28] K.A. Son, B. Yang, N. Prokopuk, J.S. Moon, A. Liao, T.M. Katona, M.A. Khan, RF GaIn HEMT sensors for detection of caustic chemicals, *IEEE Sensors J.* 11 (2011) 3476–3478, <https://doi.org/10.1109/JSEN.2011.2160978>.
- [29] Y. Xi, L. Liu, F. Ren, S.J. Pearton, J. Kim, A. Dabiran, P.P. Chow, Methane detection using Pt-gated AlGaIn/GaN high electron mobility transistor based Schottky diodes, *J. Vac. Sci. Technol. B* 31 (2013) 032203, <https://doi.org/10.1116/1.4803743>.
- [30] J. Schallwig, G. Müller, M. Eickhoff, O. Ambacher, M. Stutzmann, Gas sensitive GaN/AlGaIn-heterostructures, *Sens. Actuators B* 87 (2002) 425–430, [https://doi.org/10.1016/S0925-4005\(02\)00292-7](https://doi.org/10.1016/S0925-4005(02)00292-7).
- [31] J.-F. Xiao, C.-P. Hsu, I. Sarangadharan, G.-Y. Lee, J.-I. Chyi, Y.-L. Wang, Pt/GaN schottky diodes for highly sensitive hydrogen sulfide detection, *ECS J. Solid State Sci. Technol.* 5 (2016) Q137–Q139, <https://doi.org/10.1149/2.0311605jss>.
- [32] Z. Darmastuti, M. Andersson, L. Ojamäe, A.L. Spetz, M. Larsson, N. Lindqvist, SiC based Field effect transistor for H<sub>2</sub>S detection, 2011 IEEE SENSORS Proceedings (2011) 770–773, <https://doi.org/10.1109/ICSENS.2011.6127411>.
- [33] R. Sokolovskij, E. Iervolino, C. Zhao, F. Santagata, F. Wang, H. Yu, P.M. Sarro, G.Q. Zhang, Pt-AlGaIn/GaN HEMT-sensor for hydrogen sulfide (H<sub>2</sub>S) detection, *Proceedings of Eurosensors 2017* 1 (2017) 463, <https://doi.org/10.3390/proceedings1040463>.
- [34] O. Ambacher, J. Smart, J.R. Shealy, N.G. Weimann, K. Chu, M. Murphy, W.J. Schaff, L.F. Eastman, R. Dimitrov, L. Wittmer, M. Stutzmann, W. Rieger, J. Hilsenbeck, Two-dimensional electron gases induced by spontaneous and piezoelectric polarization charges in N- and Ga-face AlGaIn/GaN heterostructures, *J. Appl. Phys.* 85 (1999) 3222–3333, <https://doi.org/10.1063/1.369664>.
- [35] R. Sohal, P. Dudek, O. Hilt, Comparative study of NH<sub>4</sub>OH and HCl etching behaviours on AlGaIn surfaces, *Appl. Surf. Sci.* 256 (2010) 2210–2214, <https://doi.org/10.1016/j.apsusc.2009.09.075>.
- [36] R. Sokolovskij, E. Iervolino, C. Zhao, F. Wang, H. Yu, F. Santagata, P.M. Sarro, G.Q. Zhang, Pt-AlGaIn/GaN HEMT-sensor layout optimization for enhancement of hydrogen detection, 2017 IEEE SENSORS (2017) 1–3, <https://doi.org/10.1109/ICSENS.2017.8234419>.
- [37] Y.H. Kahng, R.G. Tobin, R. Looee, R.N. Ghosh, Sulfur surface chemistry on the platinum surface of a silicon carbide based hydrogen sensor, *J. Appl. Phys.* 102 (2007) 064505, <https://doi.org/10.1063/1.2779288>.
- [38] A. Ortiz-Conde, F.J. García-Sánchez, J. Muci, A. Terán Barrios, J.J. Liou, C.-S. Ho, Revisiting MOSFET threshold voltage extraction methods, *Microelectron. Reliab.* 53 (2013) 90–104, <https://doi.org/10.1016/j.microrel.2012.09.015>.
- [39] D.R. Alfonso, First-principles studies of H<sub>2</sub>S adsorption and dissociation on metal surfaces, *Surf. Sci.* 602 (2008) 2758–2768, <https://doi.org/10.1016/j.susc.2008.07.001>.
- [40] O. Weidemann, M. Hermann, G. Steinhoff, H. Wingbrant, A. Lloyd Spetz, M. Stutzmann, M. Eickhoff, Influence of surface oxides on hydrogen-sensitive Pd:GaIn Schottky diodes, *Appl. Phys. Lett.* 83 (2003) 773–775, <https://doi.org/10.1063/1.1593794>.
- [41] T. Tsung-Han, C. Huey-Ing, L. Kun-Wei, H. Ching-Wen, H. Chia-Hao, C. Tzu-Pin, C. Li-Yang, C. Kuei-Yi, C. Chung-Fu, L. Wen-Chau, Hydrogen sensing characteristics of a Pd/AlGaIn/GaN schottky diode, *Appl. Phys. Express* 1 (2008) 041102, <https://doi.org/10.1143/APEX.1.041102>.

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