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# Effect of Hot Electron Stress on AlGa<sub>N</sub>/Ga<sub>N</sub> HEMTs of Hydrogen Poisoning

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**ABSTRACT** We have investigated the effect of hot electron stress on the electrical properties of AlGa<sub>N</sub>/Ga<sub>N</sub> high electron mobility transistors (HEMTs) of hydrogen poisoning. The AlGa<sub>N</sub>/Ga<sub>N</sub> HEMTs were biased at the semi-on state, and they suffered from the hot electron stress. The devices of hydrogen poisoning were degraded, while there is almost no degradation for the fresh ones. The hot electron stress leads to the significantly positive shift of threshold voltage and the notable decrease of drain-to-source current for the AlGa<sub>N</sub>/Ga<sub>N</sub> HEMTs of hydrogen poisoning. For the AlGa<sub>N</sub>/Ga<sub>N</sub> HEMTs of hydrogen poisoning, the trap density increases by about one order of magnitude after the hot electron stress experiment. The physical mechanism can be attributed to electrically active traps due to the dehydrogenation of passivated point defects at AlGa<sub>N</sub> surface, AlGa<sub>N</sub> barrier layer, and heterostructure interface. The results of this paper may be useful in the design and application of AlGa<sub>N</sub>/Ga<sub>N</sub> HEMTs.

**INDEX TERMS** Ga<sub>N</sub> HEMT, hydrogen poisoning, hot electron stress.

## I. INTRODUCTION

Owing to its large band gap, high breakdown electric field and large two-dimensional electron gas (2DEG) concentration [1], [2], there are potential applications in high-temperature, high-frequency and high-power field for Ga<sub>N</sub> high electron mobility transistors (HEMTs). As we already know, the effect of hydrogen poisoning on device stability and reliability is important, especially if the devices are planned for space applications. In hermetically sealed packages, there would be hydrogen released from packaging material, and the devices in the hermetically sealed packages would be fully exposed to the hydrogen. The electrical characteristics of the devices could be altered, leading to their eventual failure due to hydrogen diffusion into the devices [3]. Thus there is a serious reliability concern for III-V field-effect transistors induced by hydrogen [4]–[9], such as InP HEMTs, GaAs PHEMTs, and GaAs MMICs. This is named as the hydrogen poisoning behavior for these

types of devices. The hydrogen poisoning phenomenon of AlGa<sub>N</sub>/Ga<sub>N</sub> HEMTs has been reported in our previous work [10], where there was a significantly negative shift of threshold voltage. The worst case for hot electron effect in AlGa<sub>N</sub>/Ga<sub>N</sub> HEMTs may be biased at the semi-ON state or ON state [11]–[14]. Previous investigations mainly show that the semi-ON bias condition is typically the worst case for hot electron stress (HES) in AlGa<sub>N</sub>/Ga<sub>N</sub> HEMTs [11]–[13]. In this work, both of the fresh and hydrogen poisoning AlGa<sub>N</sub>/Ga<sub>N</sub> HEMTs were biased at the semi-ON state for hot electron stress (HES) experiment.

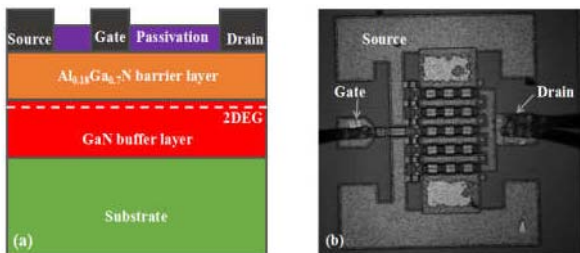
Degradation of AlGa<sub>N</sub>/Ga<sub>N</sub> HEMTs under operating conditions remains a major issue. In particular, hot electron stress (HES) can trigger on-state degradation by generating defects [15]–[17], which is consistently cited as one of the most relevant mechanisms that would limit the performance and reliability of the devices [18], [19]. Furthermore, low frequency noise (LFN) is a useful technique to characterize

the defects in microelectronic devices [20], [21], and there are extensive series of LFN investigations on the Si and SiC based MOS transistors, and AlGaIn/GaN HEMTs [22].

In this letter, the effect of hot electron stress on the electrical characteristics of AlGaIn/GaN HEMTs with hydrogen poisoning was investigated. The variation of defect density was analyzed using the LFN method. The corresponding physical mechanism for the effect of hot electron stress on hydrogen poisoned devices was also discussed. The results may provide useful guidelines in the space application of AlGaIn/GaN HEMTs.

## II. EXPERIMENTAL

The AlGaIn/GaN HEMTs were fabricated [23], and the device structure was shown in Fig. 1. The schematic diagram of cross section of the AlGaIn/GaN HEMTs is shown in Fig. 1(a). The devices have a gate length of 0.5  $\mu\text{m}$ , a gate width of 1.25 mm, and a gate-source and gate-drain spacing of 2  $\mu\text{m}$  and 5  $\mu\text{m}$ , respectively. A SiNx layer of 150 nm was grown on the surface to passivate devices. The surface morphology of AlGaIn/GaN HEMTs is shown in Fig. 1(b). The dies were placed in a chamber for 1 week at room temperature, where the ambient was  $H_2$  gas with one atmospheric pressure. Here, this is denoted as the worst hydrogen poisoning process. The electrical properties were characterized by semiconductor device analyzer (Agilent B1500A). The devices were biased at a drain-source voltage of 30 V by power instrument (Agilent E3645A) and the drain-source current ( $I_{ds}$ ) of 200 mA, which is denoted as HES experiment. LFNs were measured by SR785 dynamic signal analyzer in connection with the filters and amplifiers (Proplus 9812B).

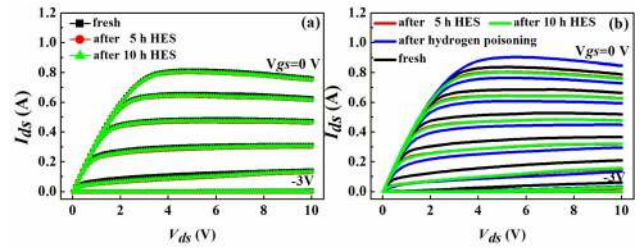


**FIGURE 1.** Device structure: (a) the schematic diagram of cross section and (b) surface morphology of AlGaIn/GaN HEMTs.

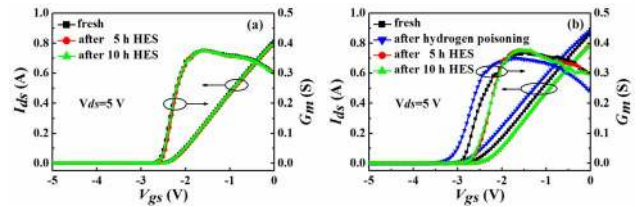
## III. RESULTS AND DISCUSSION

### A. EFFECT OF HES ON ELECTRICAL CHARACTERISTICS OF AlGaIn/GaN HEMTs OF HYDROGEN POISONING

To determine the effect of hot electron stress on the electrical properties of AlGaIn/GaN HEMTs of hydrogen poisoning, the output characteristics were measured for the fresh AlGaIn/GaN HEMTs and the ones of hydrogen poisoning for comparison, as shown in Fig. 2. As for the typical fresh AlGaIn/GaN HEMT, no variation could be observed from the output characteristics of the devices after 5 h or 10 h experiments of HES as shown in Fig. 2(a) where the gate-to-source



**FIGURE 2.** The typical output characteristics of AlGaIn/GaN HEMTs: (a) fresh devices and (b) the hydrogen poisoning devices.



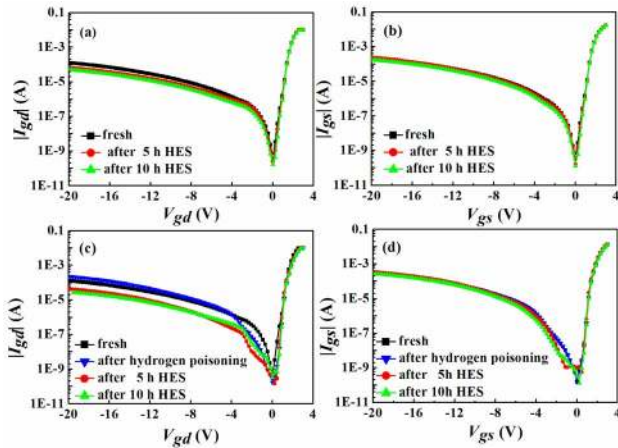
**FIGURE 3.** The typical transfer characteristics of AlGaIn/GaN HEMTs with drain-to-source voltage of 5 V step: (a) fresh and (b) with hydrogen poisoning.

voltage ( $V_{gs}$ ) is ranging from  $-3.0$  V to 0 V with a step of 0.5 V. However, as for the AlGaIn/GaN HEMTs of hydrogen poisoning as shown in Fig. 2(b), the output characteristics of the devices were obviously influenced by the 5 h or 10 h experiments of HES. As for the AlGaIn/GaN HEMTs after hydrogen poisoning, the  $I_{ds}$  values (blue line) are obviously larger than those of the fresh ones at the same  $V_{gs}$ , which are in good agreement with our previous results [10]. It could be interesting to find that after 5 h experiment of HES, the  $I_{ds}$  values (red line) of the AlGaIn/GaN HEMTs are smaller than those of the ones of hydrogen poisoning (blue line) and eventually the fresh ones (black line). Under the conditions of  $V_{gs} = 0$  V and  $V_{ds} = 5$  V, the typical  $I_{ds}$  value increases from 833 mA to 915 mA, and the maximum variation of  $I_{ds}$  is up to 82 mA for the AlGaIn/GaN HEMTs after hydrogen poisoning. However, after 5 h experiment of HES, the typical  $I_{ds}$  value decreases from 915 mA to 788 mA, and the maximum variation of  $I_{ds}$  is up to 127 mA. It indicates that the effect of HES on the devices of hydrogen poisoning is notable. Furthermore, there is little variation after 10 h experiment of HES.

As for the fresh AlGaIn/GaN HEMTs, there is almost no variation of transfer characteristics ( $I_{ds}$ - $V_{gs}$ ) and transconductance ( $G_m$ ) after 5 h or 10 h experiments of HES as shown in Fig. 3 (a), where the drain-to-source voltage ( $V_{ds}$ ) was set as 5 V. However, as for the AlGaIn/GaN HEMTs after hydrogen poisoning as shown in Fig. 3(b), there are variations of transfer characteristics and transconductance after 5 h or 10 h experiments of HES. For typical fresh AlGaIn/GaN HEMT is of a threshold voltage ( $V_{th}$ ) of  $-2.45$  V, and a maximum transconductance ( $G_{mmax}$ ) of 0.35 S. There was a negative shift for the  $I_{ds}$ - $V_{gs}$  curves and  $G_m$  curves, and the typical  $V_{th}$  changes from  $-2.45$  V to  $-2.77$  V after

hydrogen poisoning, which is in agreement with our previous results [10]. Interestingly, after 5 h experiment of HES, there was a positive shift for the  $I_{ds}$ - $V_{gs}$  curves and  $G_m$  curves, and the  $V_{th}$  value of AlGaIn/GaN HEMTs is larger than that of the hydrogen poisoning ones, and eventually larger than the fresh ones. The typical  $V_{th}$  shifts from  $-2.77$  V to  $-2.11$  V, and the typical  $G_{mmax}$  value increases from 0.25 S to 0.36 S. The maximum variation of  $G_{mmax}$  is up to 0.11 S for the AlGaIn/GaN HEMTs of hydrogen poisoning due to HES. Moreover, there is little variation after 10 h experiment of HES.

The gate-leakage currents of the fresh AlGaIn/GaN HEMTs and the ones of hydrogen poisoning were obtained as shown in Fig. 4. From Fig. 4 (a), no obvious variation could be observed on the gate-to-drain ( $I_{gd}$  - $V_{gd}$ ) curves of the fresh AlGaIn/GaN HEMTs before and after 5 h or 10 h experiments of HES. From Fig. 4 (b), there is also no obvious variation on the gate-to-source ( $I_{gs}$ - $V_{gs}$ ) curves of the fresh AlGaIn/GaN HEMTs before and after 5 h or 10 h experiments of HES. As shown in Fig. 4 (c), the gate-leakage current of the AlGaIn/GaN HEMTs of hydrogen poisoning is similar to the fresh ones. However, after the 5 h or 10 h experiments of HES, the gate-leakage current becomes smaller, which indicates that the HES has an effect on gate-to-drain leakage current of the devices of hydrogen poisoning. As shown in Fig. 4 (d), the gate leakage current of AlGaIn/GaN HEMTs of hydrogen poisoning is similar to that of the fresh ones. Furthermore, the HES have no obvious impact on  $I_{gs}$  of the hydrogen poisoning devices.



**FIGURE 4.** Schottky characteristics after HES: (a)  $I_{gd}$ - $V_{gd}$  and (b)  $I_{gs}$ - $V_{gs}$  for the fresh devices, (c)  $I_{gd}$ - $V_{gd}$  and (d)  $I_{gs}$ - $V_{gs}$  for the hydrogen poisoning devices.

## B. EFFECT OF HES ON LOW FREQUENCY NOISE OF AlGaIn/GaN HEMTs OF HYDROGEN POISONING

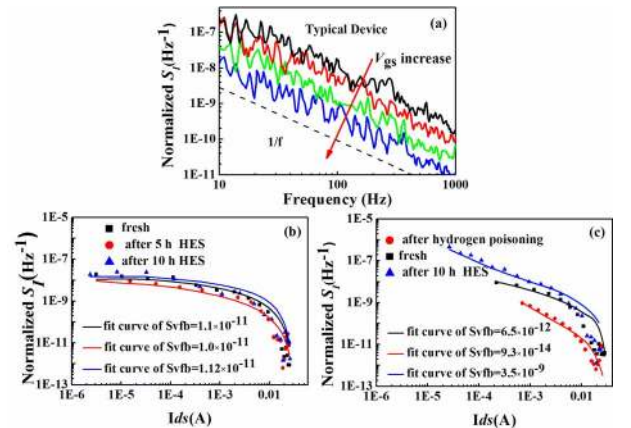
To analyze the effect of hot electron stress on the defect in AlGaIn/GaN HEMTs of hydrogen poisoning, the low frequency noise spectrum were obtained under various gate bias voltages. The current spectral noise density ( $S_I$ ) was measured at low drain bias ( $V_{ds} = 0.1$  V) as shown in Fig. 5.

The normalized  $S_I/I^2$  is  $1/f$  with the frequency in the range of 10 Hz to 1 kHz for the typical AlGaIn/GaN HEMT as shown in Fig. 5 (a). The normalized current spectral density  $S_I/I^2$  taken at 25 Hz is plotted in Fig. 5 (b) versus the current of the fresh AlGaIn/GaN HEMTs before and after 5 h or 10 h experiments of HES. The number fluctuation model explains the  $1/f$  noise by the charge trapping/detrapping of mobile carriers between interfacial traps and the channel. Based on this model, the  $S_I/I^2$  can be modeled by [22]:

$$S_I/I^2 = (g_m/I)^2 S_{vbf} \quad (1)$$

where  $S_{vbf}$  as input-referred spectral noise density was adjusted here to achieve a good fit to the data, and  $g_m/I_d$  extracted from the measured characteristics. The  $S_{vbf}$  are  $1.1 \times 10^{-11}$ ,  $1.0 \times 10^{-11}$ , and  $1.12 \times 10^{-11}$  for the fresh AlGaIn/GaN HEMTs, after 5 h and 10 h experiments of HES, respectively. Then, it was possible to determine the density of traps ( $N_t$ ) by:

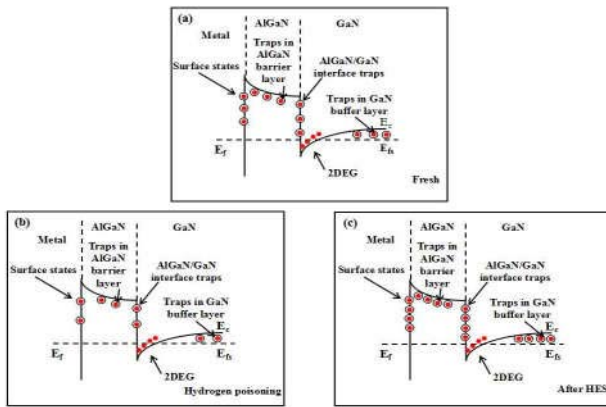
$$S_{vbf} = q^2 k T \lambda N_t / W L f C_b^2 \quad (2)$$



**FIGURE 5.** The characteristics of low frequency noise for AlGaIn/GaN HEMT: (a) the typical  $S_I/I^2$  versus frequency for the fresh devices, and (b) the  $S_I/I^2$  at 25 Hz versus  $I$  (b) for the fresh ones and (c) with hydrogen poisoning.

where  $\lambda = 0.5$  nm is the AlGaIn/GaN conduction band alignment,  $W$  and  $L$  are the gate width and length, respectively, and  $C_b$  is the AlGaIn barrier capacitance [22]. From the equation, as a first order estimate, the extracted  $N_t$  are  $6.2 \times 10^{17}$ ,  $5.7 \times 10^{17}$ , and  $6.3 \times 10^{17} \text{ cm}^{-3} \text{ eV}^{-1}$  for the fresh AlGaIn/GaN HEMTs, and after 5 h or 10 h experiments of HES, respectively. Due to the perfect material except for the surface in Si-based devices, volume traps and crystal defects are almost negligible. Therefore,  $N_t$  mainly attributed to the contribution of the traps at the interface between the gate dielectric and the Si surface or the traps in the gate dielectric [24], [25]. However,  $N_t$  is considered to be the volume trap density in the GaN buffer layer (or AlGaIn barrier) by ignoring the trapping effect of gate dielectric in AlGaIn/GaN MISHFET [25]. In our work, the  $N_t$  is also considered to be the volume trap density in the GaN buffer layer (or AlGaIn barrier) of AlGaIn/GaN HEMTs.





**FIGURE 6.** Schematic diagram of the physical mechanism for the effect of HES on hydrogen poisoning AlGa<sub>N</sub>/Ga<sub>N</sub> HEMTs: (a) lot of traps at the surface, barrier layer, and interface for the fresh device, (b) less traps for the hydrogen poisoning device, and (c) more traps for the hydrogen poisoning device after the HES experiment.

As for the AlGa<sub>N</sub>/Ga<sub>N</sub> HEMTs of hydrogen poisoning as shown in Fig. 5 (c), the  $S_{ybf}$  are  $6.5 \times 10^{-12}$ ,  $9.3 \times 10^{-14}$ , and  $3.5 \times 10^{-9}$  for the fresh AlGa<sub>N</sub>/Ga<sub>N</sub> HEMTs, hydrogen poisoning, and after 10 h experiments of HES, respectively. The extracted  $N_t$  is  $3.7 \times 10^{17}$ ,  $5.3 \times 10^{15}$ , and  $1.9 \times 10^{20} \text{cm}^{-3} \text{eV}^{-1}$ , respectively. The defect density decreases by about two orders of magnitude for the AlGa<sub>N</sub>/Ga<sub>N</sub> HEMTs after hydrogen poisoning, while it increases by about three orders of magnitude for the devices of hydrogen poisoning after 10 h experiments of HES.

### C. MECHANISM OF HES EFFECT ON AlGa<sub>N</sub>/Ga<sub>N</sub> HEMTs OF HYDROGEN POISONING

The physical mechanism could be explained as shown in Fig. 6. At the AlGa<sub>N</sub> surface, the AlGa<sub>N</sub> barrier layer, and the heterostructure interface of the fresh AlGa<sub>N</sub>/Ga<sub>N</sub> HEMTs, there are several kinds of defects [26], such as nitrogen antisite ( $N_{Ga}$ ), Ga vacancy ( $V_{Ga}$ ), N vacancy ( $V_N$ ), oxygen impurity centers ( $O_N$ ), or Ga-N divacancy ( $V_{Ga}V_N$ ) as shown in Fig. 6 (a). As for the AlGa<sub>N</sub>/Ga<sub>N</sub> HEMTs with hydrogen treatment, H would diffuse into the AlGa<sub>N</sub> barrier layer and the interface to passivate the defects [27]–[29], and there would be the hydrogenated defects [30], such as  $[V_{Ga}H_3]^0$ , antisite  $[N_{Ga}H_2]^0$ , and  $[V_{Ga}V_NH_3]^-$ . This results in the decrease of defect [27], [31], as shown in Fig. 6(b), and it is supported by the extracted  $N_t$  results (red line) as shown in Fig. 5 (c). This leads to the degradation of transconductance and negative shift of threshold voltage as shown in Fig. 3 (b) (blue line). During the experiment of HES, hot electrons with energy higher than an activation threshold could release hydrogen atom [30], and convert the  $[V_{Ga}H_3]^0$  to the  $[V_{Ga}H_2]^-$  or  $[V_{Ga}H_2]^-$ , the  $[V_{Ga}V_NH_3]^-$  to the  $[V_{Ga}V_NH_2]^{2-}$  or  $[V_{Ga}V_NH]^{3-}$ , the  $[N_{Ga}H_2]^0$  to the  $[N_{Ga}H]^-$ . This could create electrically active traps by dehydrogenation of passivated point defects [30], [32]–[35]. Therefore, the trap density increases as shown in Fig. 6 (c), and it is confirmed by the results of the extracted  $N_t$  (blue

line) as shown in Fig. 5 (c). Meanwhile, this leads to the recovery of transconductance and positive shift of threshold voltage as shown in Fig. 3 (b) (red and green lines).

### IV. CONCLUSION

The effect of hot electron on the hydrogen poisoning behavior of HEMTs was investigated, and the threshold voltage shifts positively for the AlGa<sub>N</sub>/Ga<sub>N</sub> HEMTs with hydrogen poisoning due to HES. It results in smaller drain-to-source current of AlGa<sub>N</sub>/Ga<sub>N</sub> HEMTs with hydrogen poisoning. Furthermore, trap density increases in the AlGa<sub>N</sub>/Ga<sub>N</sub> HEMTs. The corresponding physical mechanism for HES-dependent behavior could be attributed to the increase electrically active traps due to the dehydrogenation of passivated point defects, such as converting  $[V_{Ga}H_3]^0$  to  $[V_{Ga}H_2]^-$ ,  $[V_{Ga}V_NH_3]^-$  to  $[V_{Ga}V_NH_2]^{2-}$ ,  $[N_{Ga}H_2]^0$  to  $[N_{Ga}H]^-$ , etc. The results may provide useful guidelines in the space application of AlGa<sub>N</sub>/Ga<sub>N</sub> HEMTs.

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