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Effect of Hot Electron Stress on AlGaN/GaN HEMTs of Hydrogen Poisoning

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ABSTRACT We have investigated the effect of hot electron stress on the electrical properties of AlGaN/GaN high electron mobility transistors (HEMTs) of hydrogen poisoning. The AlGaN/GaN 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 AlGaN/GaN HEMTs of hydrogen poisoning. For the AlGaN/GaN 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 AlGaN surface, AlGaN barrier layer, and heterostructure interface. The results of this paper may be useful in the design and application of AlGaN/GaN HEMTs.

INDEX TERMS GaN 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 GaN 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 AlGaN/GaN 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 AlGaN/GaN 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 AlGaN/GaN HEMTs [11]–[13]. In this work, both of the fresh and hydrogen poisoning AlGaN/GaN HEMTs were biased at the semi-ON state for hot electron stress (HES) experiment.

Degradation of AlGaN/GaN 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 AlGaN/GaN HEMTs [22].

In this letter, the effect of hot electron stress on the electrical charateristics of AlGaN/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 AlGaN/GaN HEMTs.

II. EXPERIMENTAL

The AlGaN/GaN HEMTs were fabricated [23], and the device structure was shown in Fig. 1. The schematic diagram of cross section of the AlGaN/GaN HEMTs is shown in Fig. 1(a). The devices have a gate length of 0.5 µm, a gate width of 1.25 mm, and a gate-source and gate-drain spacing of 2 µm and 5 µm, respectively. A SiNx layer of 150 nm was grown on the surface to passivate devices. The surface morphology of AlGaN/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).

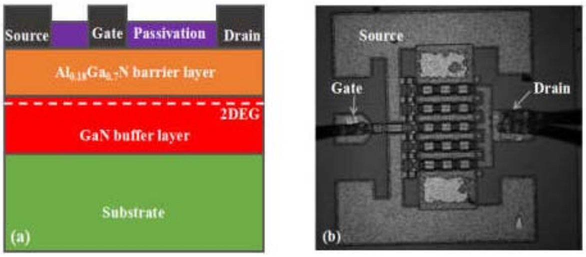

FIGURE 1. Device structure: (a) the schematic diagram of cross section and (b) surface morphology of AlGaN/GaN HEMTs.

III. RESULTS AND DISCUSSION

A. EFFECT OF HES ON ELECTRICAL CHARACTERISTICS OF AlGaN/GaN HEMTS OF HYDROGEN POISONING

To determine the effect of hot electron stress on the electrical properties of AlGaN/GaN HEMTs of hydrogen poisoning, the output characteristics were measured for the fresh AlGaN/GaN HEMTs and the ones of hydrogen poisoning for comparison, as shown in Fig. 2. As for the typical fresh AlGaN/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 voltage (V_{gs}) is ranging from −3.0 V to 0 V with a step of 0.5 V. However, as for the AlGaN/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 AlGaN/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 AlGaN/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 AlGaN/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.

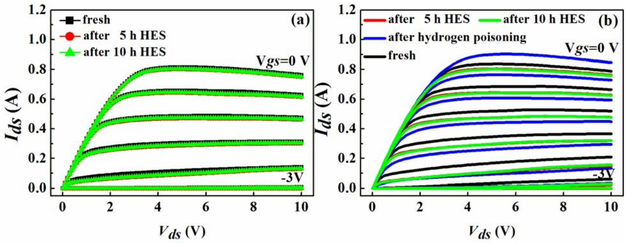

FIGURE 2. The typical output characteristics of AlGaN/GaN HEMTs: (a) fresh devices and (b) the hydrogen poisoning devices.

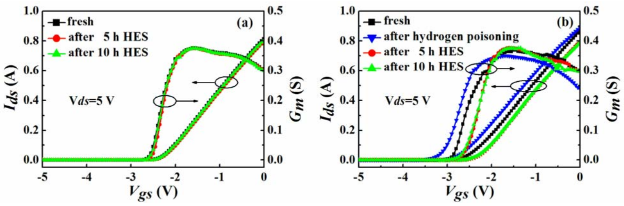

FIGURE 3. The typical transfer characteristics of AlGaN/GaN HEMTs with drain-to-source voltage of 5 V step: (a) fresh and (b) with hydrogen poisoning.

As for the fresh AlGaN/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 AlGaN/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 AlGaN/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 AlGaN/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 AlGaN/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 AlGaN/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 AlGaN/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 AlGaN/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 AlGaN/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 AlGaN/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.

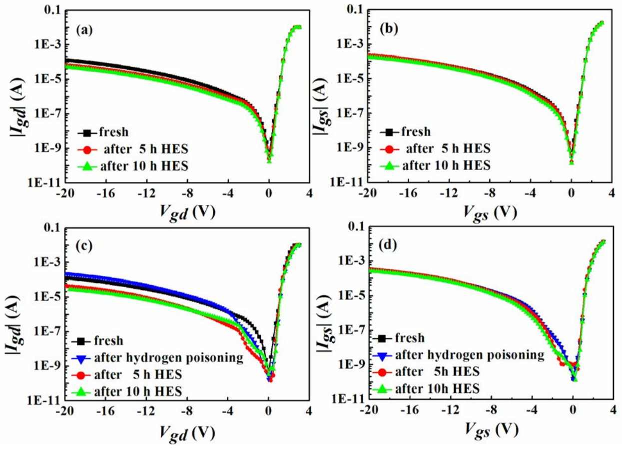

FIGURE 4. Schottky characteristics after HES: (a) I_{gd}-V_{gd} and (b) I_{gs}-V_{gs} for the fresh devices, (c) I_{gd}-V_{gd} and (d) I_{gs}-V_{gs} for the hydrogen poisoning devices.

B. EFFECT OF HES ON LOW FREQUENCY NOISE OF AlGaN/GaN HEMTS OF HYDROGEN POISONING

To analyze the effect of hot electron stress on the defect in AlGaN/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 AlGaN/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 AlGaN/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]:

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

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 1.1×10^{-11}, 1.0×10^{-11}, and 1.12×10^{-11} for the fresh AlGaN/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:

$$S_{vbf} = q^2 kT\lambda N_t/WLfC_b^2 \tag{2}$$

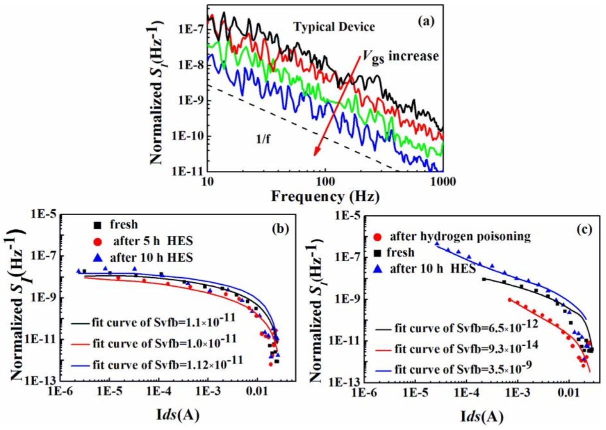

FIGURE 5. The characteristics of low frequency noise for AlGaN/GaN HEMT: (a) the typical S_I/I^2 versus frequency for the fresh devices, and (b) the S_I/I^2 at 25 Hz versus I (b) for the fresh ones and (c) with hydrogen poisoning.

where $\lambda = 0.5$ nm is the AlGaN/GaN conduction band alignment, W and L are the gate width and length, respectively, and C_b is the AlGaN barrier capacitance [22]. From the equation, as a first order estimate, the extracted N_t are 6.2×10^{17}, 5.7×10^{17}, and $6.3\times10^{17}\text{cm}^{-3}\text{eV}^{-1}$ for the fresh AlGaN/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 AlGaN barrier) by ignoring the trapping effect of gate dielectric in AlGaN/GaN MISHFET [25]. In our work, the N_t is also considered to be the volume trap density in the GaN buffer layer (or AlGaN barrier) of AlGaN/GaN HEMTs.

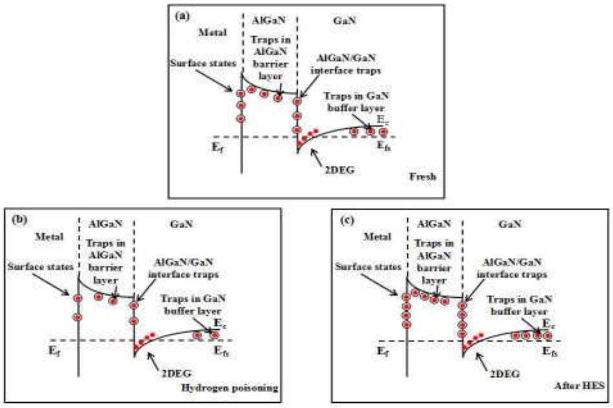

FIGURE 6. Schematic diagram of the physical mechanism for the effect of HES on hydrogen poisoning AlGaN/GaN HEMTs: (a) lot of traps at the surface, barrier layer, and interface for the fresh device, (b) less traps for the hydrogen poisoning device, and (c) more traps for the hydrogen poisoning device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

As for the AlGaN/GaN HEMTs of hydrogen poisoning as shown in Fig. 5 (c), the S_{vbf} are 6.5×10^{-12}, 9.3×10^{-14}, and 3.5×10^{-9} for the fresh AlGaN/GaN HEMTs, hydrogen poisoning, and after 10 h experiments of HES, respectively. The extracted N_t is 3.7×10^{17}, 5.3×10^{15}, and $1.9\times10^{20}\text{cm}^{-3}\text{eV}^{-1}$, respectively. The defect density decreases by about two orders of magnitude for the AlGaN/GaN 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 AlGaN/GaN HEMTS OF HYDROGEN POISONING

The physical mechanism could be explained as shown in Fig. 6. At the AlGaN surface, the AlGaN barrier layer, and the heterostructure interface of the fresh AlGaN/GaN 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 AlGaN/GaN HEMTs with hydrogen treatment, H would diffuse into the AlGaN 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 AlGaN/GaN HEMTs with hydrogen poisoning due to HES. It results in smaller drain-to-source current of AlGaN/GaN HEMTs with hydrogen poisoning. Furthermore, trap density increases in the AlGaN/GaN 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 AlGaN/GaN HEMTs.

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