ELectronics EXpress

LETTER

IEICE Electronics Express, Vol.16, No.5, 1–8

High-temperature stability of improved AlGaN/AlN/GaN HEMT with pre-gate metal treatment

Yu-Shyan Lin[a] **and Wei-Hou Goa**

Department of Materials Science and Engineering, National Dong Hwa University, 1, Sec. 2, Da Hsueh Rd., Shou-Feng, Hualien 974, Taiwan

a) *yslindh@gms.ndhu.edu.tw*

Abstract: This study proposes the investigation of using the $(NH_4)_2S_x$ solution to form the AlGaN surface passivation on the AlGaN/GaN high electron mobility transistors (HEMTs). Both treatment schemes are implemented on separate pieces of the same HEMT wafer, including $(NH_4)_2S_x$ pre-gate and post-gate metal treatments. Temperature-dependent characteristics of the HEMTs are also studied. Experimental results demonstrate that by the surface treatment prior to metal, the performance of the studied HEMTs can be improved, including thermal stability, dc and high-frequency characteristics. Furthermore, the interface state density (D_{it}) of the studied HEMT is studied by the subthreshold slope method. To the best of our knowledge, this is the first report on comparison of AlGaN/AlN/GaN HEMTs with pre-gate and post-gate metal treatments.

Keywords: GaN, HEMT, passivation, sulfide treatment, interface state density, subthreshold slpoe

Classification: Electron devices, circuits and modules

References

[1] T. B. Wang, *et al.*: "Comparison of $Al_{0.32}Ga_{0.68}N$/GaN heterostructure field-effect transistors with different channel thicknesses," J. Electrochem. Soc. **154** (2007) H131 (DOI: 10.1149/1.2409478).

[2] J. H. Tsai, *et al.*: "High-performance AlGaN/AlN/GaN high electron mobility transistor with broad gate-to-source operation voltages," Phys. Status Solidi. C **12** (2015) 596 (DOI: 10.1002/pssc.201400241).

[3] Y. S. Lin and C. C. Lu: "Improved AlGaN/GaN metal-oxide-semiconductor high-electron mobility transistors with TiO_2 gate dielectric annealed in nitrogen," IEEE Trans. Electron Devices **65** (2018) 783 (DOI: 10.1109/TED.2017.2781141).

[4] D. K. Kim, *et al.*: "Performance of AlGaN/GaN MISHFET using dual-purpose thin Al_2O_3 layer for surface protection and gate insulator," Solid-State Electron. **100** (2014) 11 (DOI: 10.1016/j.sse.2014.05.007).

[5] T. Hashizume, *et al.*: "State of the art on gate insulation and surface passivation for GaN-based power HEMTs," Mater. Sci. Semicond. Process. **78** (2018) 85 (DOI: 10.1016/j.mssp.2017.09.028).

[6] Y. S. Lin, *et al.*: "Stability study and effect of passivation on InP/InGaAs

DOI: 10.1587/elex.16.20181046
Received November 23, 2018
Accepted December 21, 2018
Publicized February 15, 2019
Copyedited March 10, 2019

double heterojunction bipolar transistors," Appl. Phys. Lett. **94** (2009) 063506 (DOI: 10.1063/1.3075842).

[7] P. H. Lai, *et al.*: "Improved temperature-dependent characteristics of a sulfur-passivated AlGaAs/InGaAs/GaAs pseudomorphic high-electron-mobility transistor," J. Electrochem. Soc. **153** (2006) G632 (DOI: 10.1149/1.2199433).

[8] P. H. Lai, *et al.*: "Influences of sulfur passivation on temperature-dependent characteristics of an AlGaAs/InGaAs/GaAs PHEMT," IEEE Trans. Electron Devices **53** (2006) 1 (DOI: 10.1109/TED.2005.860654).

[9] Y. S. Lin, *et al.*: "Performance of surface and gate engineered AlGaAs/InGaAs pseudomorphic high-electron mobility transistors," J. Electrochem. Soc. **156** (2009) H401 (DOI: 10.1149/1.3098977).

[10] Y. S. Lin, *et al.*: "Electrical, optical and surface properties of P_2S_5/$(NH_4)_2S_x$+Se-treated doped-channel field-effect transistors with double etch-stop layers," Thin Solid Films **519** (2011) 3388 (DOI: 10.1016/j.tsf.2010.12.238).

[11] M. A. Alim and A. A. Rezazadeh: "Temperature- dependent DC and small-signal analysis of AlGaAs/InGaAs pHEMT for high-frequency applications," IEEE Trans. Electron Devices **63** (2016) 1005 (DOI: 10.1109/TED.2016.2517934).

[12] J. W. Chung, *et al.*: "Effect of gate leakage in the subthreshold characteristics of AlGaN/GaN HEMTs," IEEE Electron Device Lett. **29** (2008) 1196 (DOI: 10.1109/LED.2008.2005257).

[13] R. Wang, *et al.*: "Gate-recessed enhancement-mode InAlN/AlN/GaN HEMTs with 1.9-A/mm drain current density and 800-mS/mm transconductance," IEEE Electron Device Lett. **31** (2010) 1383 (DOI: 10.1109/LED.2010.2072771).

[14] J. W. Chung, *et al.*: "Estimation of trap density in AlGaN/GaN HEMTs from subthreshold slope study," 65th Annual Device Res. Conf. (2007) 111.

[15] S. Prasad, *et al.*: "Characterization of AlGaN/GaN and AlGaN/AlN/GaN HEMTs in terms of mobility and subthreshold slope," J. Comput. Electron. **15** (2016) 172 (DOI: 10.1007/s10825-015-0751-8).

1 Introduction

III-nitride high-electron-mobility transistors (HEMTs) are of significant interest for next-generation power devices [1, 2, 3, 4, 5]. Remarkable progress of both the AlGaN/GaN materials quality and device performance has been achieved. GaN-based Schottky-gate field-effect transistors suffer from the problem of high leakage current. Integration of a gate dielectric in metal-insulator-semiconductor field-effect transistors (MISFETs) has been demonstrated to offer remarkably decreased gate leakage current [3, 4, 5]. An alternative approach for reducing the leakage current is to passivate the surface of the devices. Through the surface passivation and Schottky gate metals engineering, the device characteristics and thermal stability can be improved. Additionally, passivation of heterojunction bipolar transistors (HBTs) [6] and heterostructure field-effect transistors (HFETs) [7, 8, 9, 10] has been investigated. However, the comparison of GaN-based HEMTs with surface treatments before and after gate metal deposition has not yet to be exploited. Consequently, the effects of $(NH_4)_2S_x$ treatments before or after gate metal deposition are evaluated with regard to the electrical characteristics of the HEMTs in this study.

DOI: 10.1587/elex.16.20181046
Received November 23, 2018
Accepted December 21, 2018
Publicized February 15, 2019
Copyedited March 10, 2019

ELectronics EXpress

There is a necessity for high-temperature electronics in microwave communication system. Transistors with high-temperature characteristics and excellent thermal stability are important for high frequency and high power applications. Many research groups have reported on the high-temperature performance of the GaAs-based HEMTs [7, 8, 9, 11]. Nevertheless, little attention has been devoted to investigating the thermal stability of GaN-based HEMTs. In this study, improved device characteristics and thermal stability of the HEMTs are obtained to perform surface treatment and passivation prior to the gate metal deposition.

2 Device structure and experiments

The epitaxial growth of the studied HEMT was performed in a metalorganic chemical-vapor deposition (MOCVD) system. The top layer was an $Al_{0.25}Ga_{0.75}N$, followed by a 1.5 nm AlN layer, and a 1.5 µm GaN layer, and a buffer layer on a silicon substrate.

Mesa isolation was achieved by inductively coupled-plasma reactive ion etcher (ICP-RIE) with Ar/Cl_2 plasma reactive ion etching, followed by source/drain ohmic metallization using Ti/Al/Au (10/100/50 nm) stack deposition and rapid thermal annealing in a N_2 atmosphere. Gate metal stack, 100 nm Ni followed by 50 nm Au, is then deposited by electron beam and lifted-off in acetone. Ni has high work function so that it can increase the Schottky barrier height to suppress the leakage current to obtain high breakdown voltage. Au was used for preventing oxidation of Ni.

The samples were soaked in the ammonia-sulfide solution ($(NH_4)_2S_x$, 6%) for 10 minutes at room temperature and then rinsed in deionized water followed by blown dry N_2 gas. The HEMTs used in this exploration were treated in two different methods. The first HEMT was passivated with $(NH_4)_2S_x$ before the gate metal deposition. The second HEMT was passivated with $(NH_4)_2S_x$ after gate metal deposition. The third control HEMT without passivation treatment was also studied. The gate length and source-drain spacing of the studied HEMTs are 1 and 5 µm, respectively.

3 Results and discussion

Many features are worth noting in comparing the current–voltage characteristics for the three studied HEMTs. Fig. 1 shows the two-terminal gate-drain characteristics of our studied HEMTs. We defined the values of leakage current density at the −20 V of gate-drain voltage. The relevant device parameters at 300 K are summarized in Table I. At 300 K, the I_g value in the HEMT with pre-gate treatment is suppressed by over two orders of magnitude compared to that in the untreated HEMT.

The two-terminal gate-to-drain reverse breakdown voltage (BV_{GD}) is measured at a reverse gate-to-drain current of 1 mA/mm. The values of BV_{GD} for the HEMT with pre-gate treatment are 109 V, 96 V, 87 V, 76 V at 300 K, 360 K, 420 K, 480 K, respectively. Consequently, the temperature coefficient of BV_{GD} ($\partial BV_{GD}/\partial T$) of the HEMT with pre-gate treatment is −0.18 V/K. Temperature coefficients of the device characteristics of the studied HEMTs are tabulated in Table II. This pre-gate

DOI: 10.1587/elex.16.20181046
Received November 23, 2018
Accepted December 21, 2018
Publicized February 15, 2019
Copyedited March 10, 2019

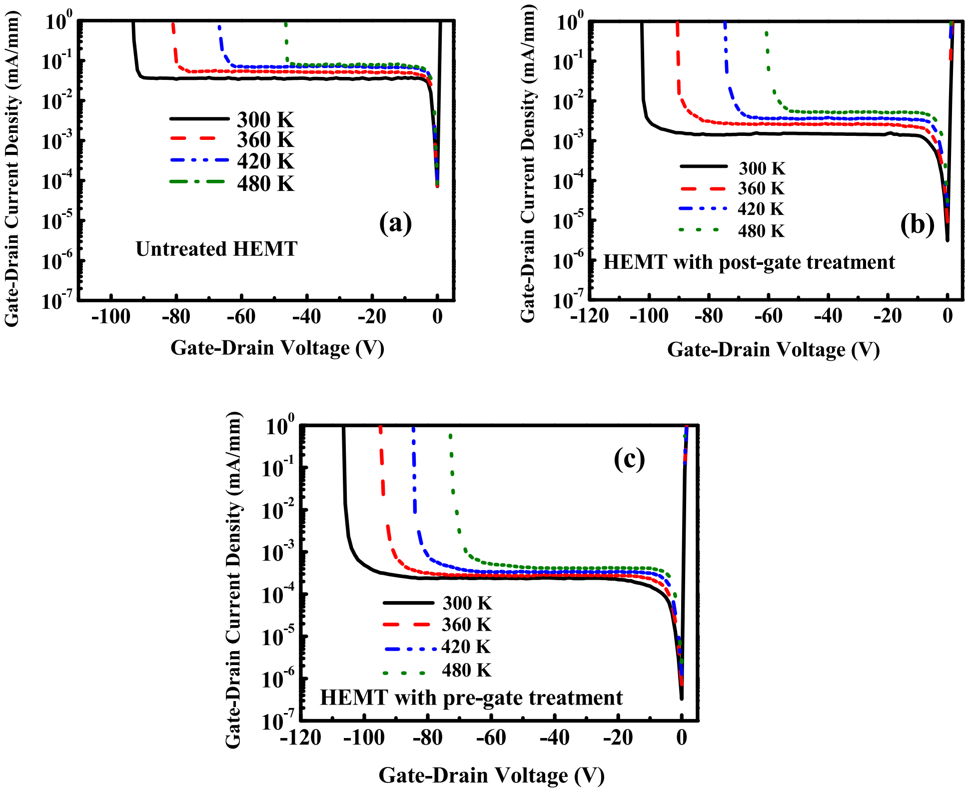

Fig. 1. Two-terminal gate-drain characteristics of the (a) untreated HEMT, (b) HEMT with post-gate treatment, and (c) HEMT with pre-gate treatment at various temperatures.

metal treatment results in a large reduction in the gate leakage, improved breakdown voltages, and thermal stability of BV_{GD}.

Fig. 2 shows the temperature dependence of the extrinsic transconductance (g_m) and drain current versus gate bias for the studied HEMTs between 300 and 480 K. The values of $g_{m,max}$ for the HEMT with pre-gate treatment are 136.6 mS/mm, 124.1 mS/mm, 109.5 mS/mm, 95.2 mS/mm at 300 K, 360 K, 420 K, and 480 K, respectively. Therefore, the temperature coefficient of $g_{m,max}$ ($\partial g_{m,max}/\partial T$) for the pre-gate treatment HEMT is −0.23 mS/mm-K. From Table II, the results demonstrate that the magnitude of the $\partial g_{m,max}/\partial T$ value for the HEMTs with pre-gate treatment is smallest of the studied HEMTs. The gate voltage swing (GVS), defined as the gate voltage range where a 10% down from its maximum g_m, is 2.5 V at 300 K for the HEMT with pre-gate treatment. Furthermore, the On/Off drain current ratio (I_{on}/I_{off}), determined as I_{on} at $V_{GS} = 2$ and I_{off} at $V_{GS} = -6$ V, is 10^6 for the untreated HEMT and 2×10^7 for the HEMT with pre-gate treatment, at $V_{DS} = 7$ V. From Table I, the On/Off drain current ratio of the HEMT with pre-gate treatment is largest due to its reduced gate leakage current [3, 12].

The values of subthreshold slope (SS) for the HEMT with pre-treatment are 132 mV/dec, 181 mV/dec, 195 mV/dec, 212 mV/dec at 300 K, 360 K, 420 K, and 480 K, respectively. The temperature coefficient of SS ($\partial SS/\partial T$) for the HEMT with pre-treatment is 0.44 $\frac{\text{mV}}{\text{dec} \cdot \text{K}}$. From Table II, the HEMT with pre-gate treatment has the smallest SS and $\partial SS/\partial T$ variation because it has the smallest leakage current in our studied HEMTs [3, 12].

DOI: 10.1587/elex.16.20181046
Received November 23, 2018
Accepted December 21, 2018
Publicized February 15, 2019
Copyedited March 10, 2019

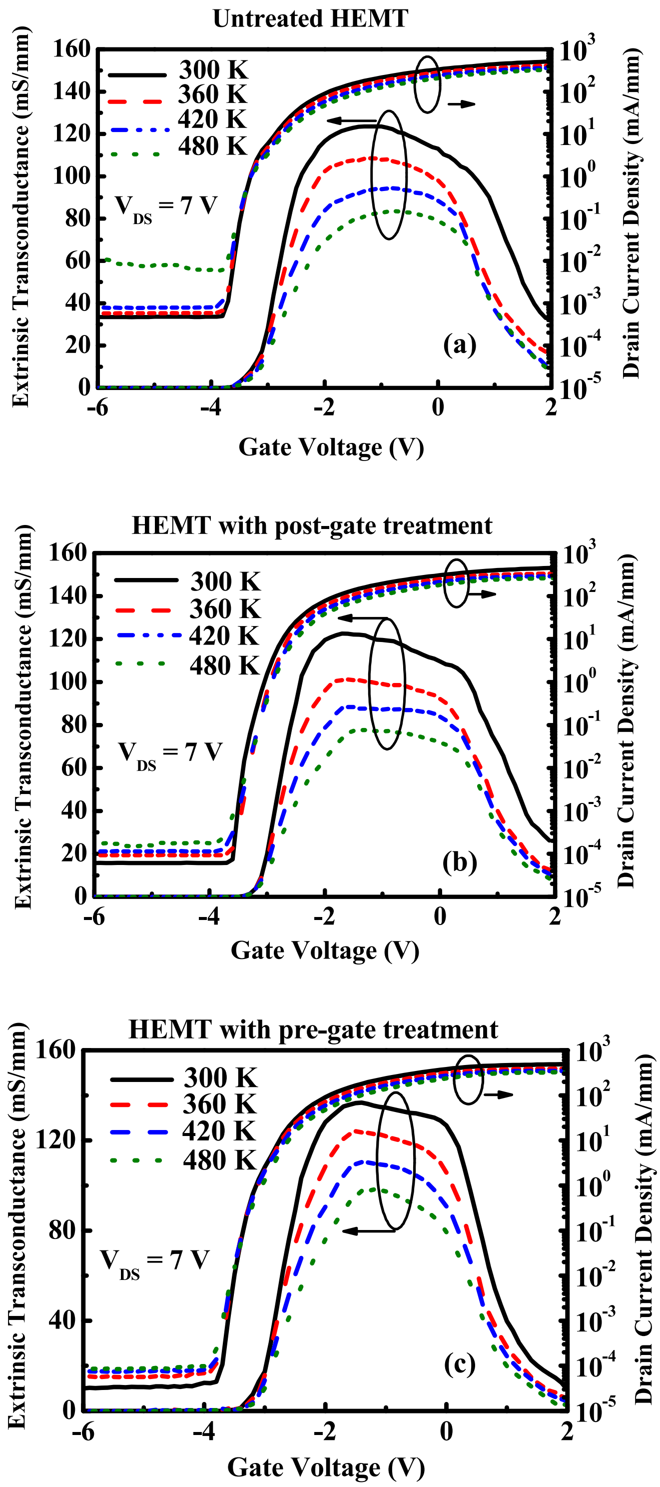

Fig. 2. Drain current and extrinsic transconductance versus gate-to-source voltage of the (a) untreated HEMT, (b) HEMT with post-gate treatment, (c) and HEMT with pre-gate treatment, at a fixed drain bias of 7 V.

The interface state density (D_{it}) under the gate of the HEMTs is characterized by the subthreshold slope (SS) method. By analogy with metal-oxide-semiconductor field-effect transistors (MOSFETs) [3], the subthreshold slope for HEMTs is given by [13, 14, 15]

DOI: 10.1587/elex.16.20181046
Received November 23, 2018
Accepted December 21, 2018
Publicized February 15, 2019
Copyedited March 10, 2019

$$SS = \frac{kT}{q}\ln(10)(1 + \varsigma) \tag{1}$$

where ς is a non-ideality factor that is related to the interface trap density; k is the Boltzmann constant; q is the electronic charge, and T is the temperature (K). From Table I, the SS value of the HEMT with pre-gate treatment is lowest among of the HEMTs studied here. This suggests that the pre-gate treatment significantly reduces the interface trap density at the AlGaN surface. A further important point arising from Eq. (1) is that the SS value increases with the temperature. The theoretical relation is consistent with our above temperature-dependent SS values.

The values of threshold voltage (V_{th}) for the HEMT with pre-treatment are −2.70 V, −2.77 V, −2.81 V, −2.87 V at 300 K, 360 K, 420 K, and 480 K, respectively. Therefore, the $\partial V_{th}/\partial T$ value for the HEMT with pre-gate treatment is −0.94 V/K. From Table II, the $\partial V_{th}/\partial T$ variation can be significantly suppressed due to the $(NH_4)_2S_x$ pre-gate metal treatment.

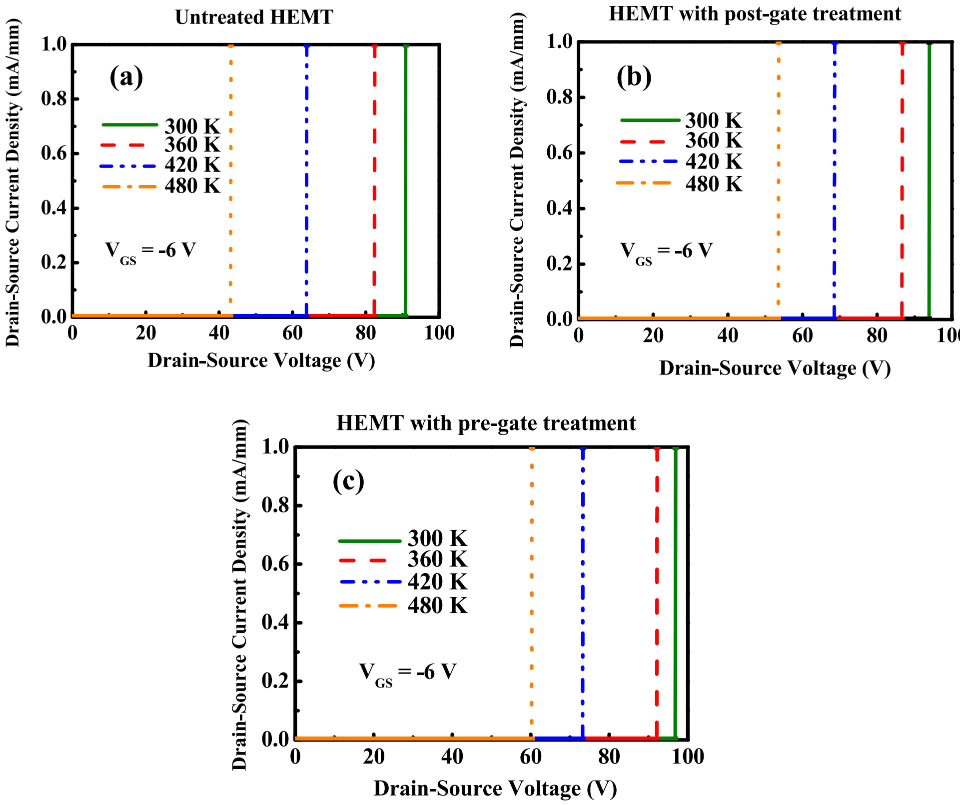

Fig. 3. Three-terminal off-state breakdown characteristics of the (a) untreated HEMT, (b) HEMT with post-gate treatment, and (c) HEMT with pre-gate treatment at various temperatures.

Fig. 3 shows the three-terminal off-state breakdown characteristics of our studied HEMTs. The criterion of the three-terminal off-state breakdown voltage (BV_{off}) is set to be an off-state drain current of 1 mA/mm. The values of BV_{off} for the HEMT with pre-gate treatment are 96.9 V, 92.2 V, 73.3 V, 60.3 V at 300 K, 360 K, 420 K, 480 K, respectively. Consequently, the temperature coefficient of BV_{off} ($\partial BV_{off}/\partial T$) of the HEMT with pre-gate treatment is −0.20 V/K. From Table II, $(NH_4)_2S_x$ pre-gate metal treatment can significantly increase BV_{off} and

DOI: 10.1587/elex.16.20181046
Received November 23, 2018
Accepted December 21, 2018
Publicized February 15, 2019
Copyedited March 10, 2019

reduce the magnitude of $\partial BV_{off}/\partial T$. Table I and Table II list the summary of device performance data for our studied HEMT.

Table I. Summary of the studied device characteristics at 300 K.

	Untreated HEMT	HEMT with post-gate treatment	HEMT with pre-gate treatment
I_g (mA/mm)	3.74×10^{-2}	1.52×10^{-3}	2.2×10^{-4}
BV_{GD} (V)	96	105	109
$g_{m,max}$ (mS/mm)	122	122.6	136.6
I_{on}/I_{off}	10^6	8.75×10^6	2×10^7
SS (mV/dec)	150	140	132
V_{th} (V)	−2.82	−2.73	−2.7
GVS (V)	2.2	2.3	2.5
BV_{off} (V)	90.9	94.0	96.9

Table II. Temperature coefficients of $g_{m,max}$, SS, V_{th}, V_{off}, and V_{GD} for our studied HEMTs.

	Untreated HEMT	HEMT with post-gate treatment	HEMT with pre-gate treatment
$\frac{\partial BV_{GD}}{\partial T}\left(\frac{V}{K}\right)$	−0.27	−0.23	−0.18
$\frac{\partial g_{m,max}}{\partial T}\left(\frac{mS}{mm \cdot K}\right)$	−0.27	−0.25	−0.23
$\frac{\partial SS}{\partial T}\left(\frac{mV}{dec \cdot K}\right)$	1.15	0.63	0.44
$\frac{\partial V_{th}}{\partial T}\left(\frac{V}{K}\right)$	−1.5	−1.1	−0.94
$\frac{\partial BV_{off}}{\partial T}\left(\frac{V}{K}\right)$	−0.27	−0.22	−0.2

On-wafer RF measurements are done on our studied HEMTs in the frequency range of 0.2–25 GHz using an HP8510C network analyzer. Fig. 4 shows the small-signal short-circuit current gain and maximum stable/available gain (MSG/MAG) measured from the studied HEMTs. The f_T values of 8.2, 8.8, and 11.2 GHz are measured for the untreated HEMT, HEMT with post-gate treatment, and HEMT with pre-gate treatment, respectively. Furthermore, the f_{max} values are 9, 10.8, and 14.8 GHz for the untreated HEMT, HEMT with post-gate treatment, and HEMT with pre-gate treatment, respectively. The experimental results demonstrate that the $(NH_4)_2S_x$ pre-gate treatment significantly improves the high-frequency characteristics.

DOI: 10.1587/elex.16.20181046
Received November 23, 2018
Accepted December 21, 2018
Publicized February 15, 2019
Copyedited March 10, 2019

IEICE Electronics Express, Vol.16, No.5, 1–8

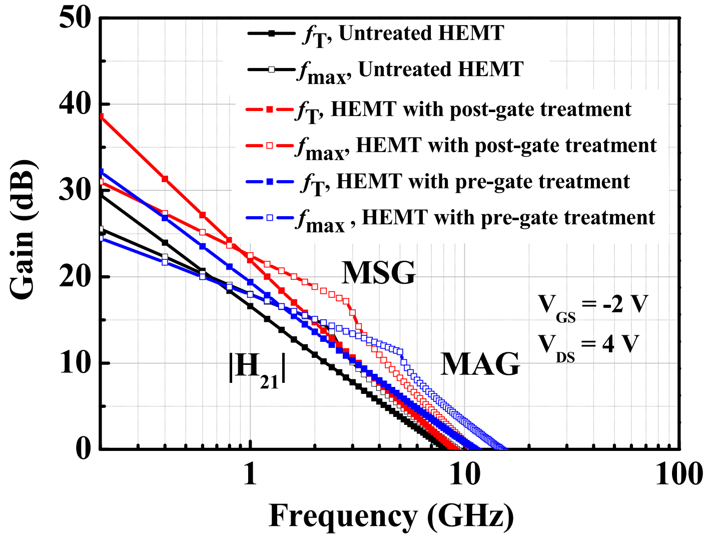

Fig. 4. Forward current gain and maximum stable gain/maximum available gain (MSG/MAG) plotted versus frequency.

4 Conclusion

In summary, the beneficial influence of $(NH_4)_2S_x$ treatment on AlGaN/AlN/GaN HEMTs is demonstrated. The surface treatment with $(NH_4)_2S_x$ before the gate metal deposition greatly reduces the gate leakage current. Furthermore, the HEMT with $(NH_4)_2S_x$ pre-gate metal treatment shows the improved device characteristics, high temperature operation capability, and relatively temperature-insensitive behaviors. These advantages suggest that the proposed sulfide treatment have high potential for the fabrication of AlGaN/GaN HEMTs.

Acknowledgments

The authors would like to thank the Ministry of Science and Technology of the Republic of China for financially supporting this research under Contract No. MOST 106-2221-E-259-259-019.

DOI: 10.1587/elex.16.20181046
Received November 23, 2018
Accepted December 21, 2018
Publicized February 15, 2019
Copyedited March 10, 2019