Effects of Low-Damage Plasma Treatment on the Channel 2DEG and Device Characteristics of AlGaN/GaN HEMTs *

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We investigate the effects of remote nitride-based plasma treatment on the channel carrier and device characteristics of AlGaN/GaN high electron mobility transistors (HEMTs). A 200 W NH_3/N_2 remote plasma causes little degeneration of carrier mobility and an increase in electron density due to surface alteration, which results in a decrease in sheet resistance and an increase in output current by 20–30%. Improved current slump, suppressed gate leakage current, and improved Schottky contact properties are also achieved by using low-damage nitride-based plasma treatment. It is found that NH_3/N_2 remote plasma treatment is a promising technique for GaN-based HEMTs to modulate the surface conditions and channel properties.

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GAN-based high electron mobility transistors (HEMTs) are promising candidates for high-frequency and high-power applications. The large current originating from a high-density two-dimensional electron gas (2DEG), along with high breakdown voltage, results in the high power delivery capability of GaN-based HEMTs. The source of 2DEG is believed to be the polarization effects and surface donor states.[1,2] Therefore, GaN-based HEMTs are sensitive to surface treatment. Various surface treatment such as rf plasma[3–11] and thermal prepassivation[12,13] have been commonly used in GaN-based HEMTs, which have demonstrated improved reliability,[4–8] removed etch damage[3] and modulated dc characteristics.[6–8,12,13] However, the rf power should be set at a low level because significant degeneration of device performance due to electrical damage can be observed with rf power larger than 60 W.[8,10]

Huang *et al.*[14,15] developed a low-damage remote plasma treatment method with a plasma-enhanced atomic layer deposition (PEALD) system, realizing excellent surface passivation and interface instability. However, the rf power was still set at a low level of 50 W, and the impacts on channel 2DEG were not studied. In this Letter, a remote nitride-based plasma with 200 W rf power is studied. Little degeneration of AlGaN/GaN 2DEG, improved surface and dc characteristics are achieved, verifying the low-damage property of remote plasma treatment.

The AlGaN/GaN heterostructures as shown in Fig. 1 were grown by metal-organic chemical vapor deposition on sapphire substrates. The epitaxial layers consist of a 180-nm-thick AlN nuclear layer, 1.3-μm un-doped GaN buffer, a 1-nm-thick AlN interlayer, 25 nm $Al_{0.3}Ga_{0.7}N$ barrier, and a 2-nm-thick GaN cap from bottom to top. Hall measurement at room temperature shows a sheet carrier density of $8\times10^{12}\,\mathrm{cm}^{-2}$ and a mobility of $1600\,\mathrm{cm}^2/\mathrm{V\cdot s}$.

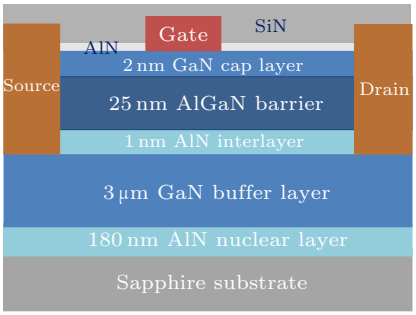

Fig. 1. Schematic cross sections of the AlGaN/GaN HEMTs used in this work.

The device process started with Ti/Al/Ni/Au Ohmic contacts by e-beam evaporation and rapid thermal annealing at 830℃ in N_2 for 30 s. Measurement with the transmission line model (TLM) showed a low Ohmic contact resistance (R_c) smaller than 0.5 Ω·mm. Then mesa isolation was achieved by Cl_2 reactive ion etching. Before passivation and gate electrodes fabrication, remote plasma treatment in PEALD was applied to the samples, with rf power of 200 W. Three types of surface treatment were studied: w/o plasma treatment, w/N_2 plasma treatment, and w/NH_3/N_2 mixed gas plasma treatment. Ni/Au/Ni gate contacts were also fabricated by lift-off process. The AlN passivation was grown by PEALD at 300℃,[16] and SiN was grown by plasma enhanced atomic layer deposition at 250℃. All devices have a gate length $L_G = 1.2\,\mu\mathrm{m}$, gate width $W_G = 50\,\mu\mathrm{m}$, and source-drain distance of 4 μm.

TLM patterns w/o passivation layers were used to investigate the impacts of plasma treatment on chan-

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nel properties. Figure 2 illustrates the output current, sheet resistance $R_{\rm sheet}$, and $R_{\rm c}$ of TLM patterns before and after plasma treatment. In order to eliminate the effect of wafer non-uniformity, three samples were analyzed for each case: S1–S3 for N_2 plasma treatment, and S4–S6 for NH_3/N_2 plasma treatment. NH_3/N_2 plasma treatment leads to a decrease in sheet resistance from $\sim$550 Ω/□ to $\sim$400 Ω/□, resulting in an increase in output current from $\sim$550 mA/mm to $\sim$700 mA/mm, while N_2 plasma treatment caused a little change in $R_{\rm sheet}$ and output current. According to the expression $R_{\rm sheet} = (qn_{\rm s}\mu_{\rm n})^{-1}$, where q is magnitude of electronic charge, $n_{\rm s}$ and $\mu_{\rm n}$ are the density and mobility of 2DEG. The decrease in $R_{\rm sheet}$ and increase in current should be due to an increase in carrier density and/or mobility.

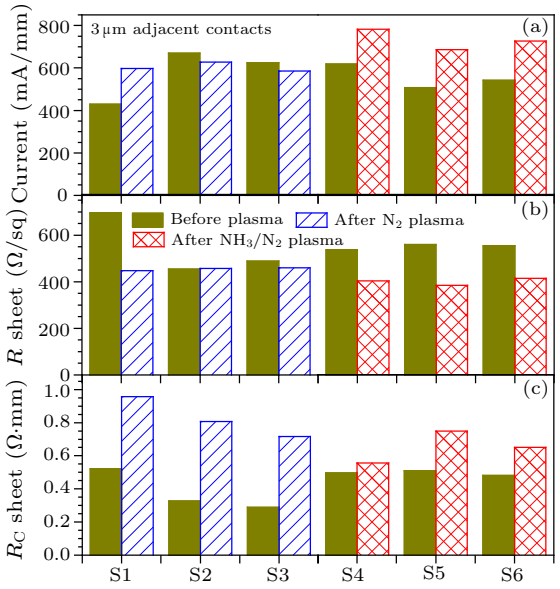

Fig. 2. Impacts of surface plasma treatment on: (a) the statistical saturated output current, (b) sheet resistance, and (c) contact resistance for TLM patterns.

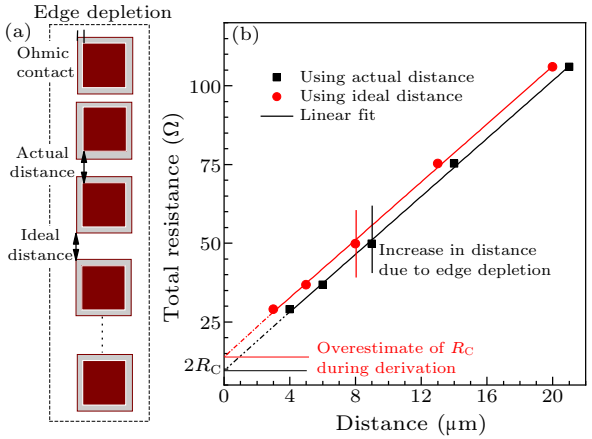

Fig. 3. (a) Schematic top view of edge depletion effect of plasma treatment on TLM patterns. (b) Sketch of overestimated $R_{\rm c}$ during TLM derivation using the ideal distance between adjacent contacts.

In addition, note that $R_{\rm c}$ increases markedly after plasma treatment. This happens because N-vacancies ($V_{\rm N}^{3+}$) in the proximity of Ti/nitride interface are critical to the foundation for tunneling contact mechanism,[17] and the 200 W nitride-based plasma may compensate for the N-vacancies near the edge of Ohmic area. X-ray photoelectron spectroscopy analysis on GaN surface shows that NH_3/N_2 plasma treatment led to an increase in N/Ga atomic ratio from 1.4 to 1.47, indicating N atoms permeating through the nitride layer during plasma treatment. The N permeating by nitride-based plasma treatment could contribute to the decrease in N-vacancies for Ohmic contacts, and result in edge depletion effect. The edge depletion of N-vacancies causes a decrease in Ohmic area (i.e., an increase in the distance between adjacent contacts), so the derivation leads to an overestimation of $R_{\rm c}$, as shown in Fig. 3. For NH_3/N_2 plasma treatment, H^+ can diffuse deeper into GaN layer than H^-, leading to the forming of $V_{\rm GaN}$–$H_{\rm n}$ complex by means of reaction with gallium vacancy ($V_{\rm Ga}^{3-}$).[18] This helps to passivate the deep level acceptors in GaN and results in a decrease in resistivity.[19] Therefore, the existence of NH_3 will cause a smaller decrease in contact resistance, partially suppressing the influence of decrease in N-vacancies.

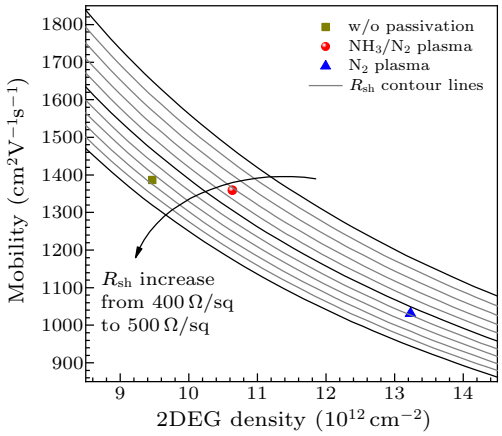

Fig. 4. Impacts of surface plasma treatment and passivation layer on the Hall measurement results of AlGaN/GaN heterostructures.

The effect of plasma treatment on the channel properties of AlGaN/GaN was further studied using a contact Hall measurement system, as shown in Fig. 4. Plasma treatment leads to an increase in $n_{\rm s}$, which should be attributed to the modification of surface barrier height and donor distribution.[20] The increase in carrier density causes more serious carrier scattering from electron collision, leading to a decrease in $\mu_{\rm n}$. NH_3/N_2 plasma treatment leads to small degeneration of $\mu_{\rm n}$ because of the additional H^+ passivation effect and the decrease in deep-level bulk defects.[4,8,18] Sheet resistance (i.e., $qn_{\rm s}{\mu_{\rm n}}^{-1}$) is used to compare the channel transport property and conductivity for different plasma treatments, as shown by the $R_{\rm sheet}$ contour lines. The nitride-based plasma treatment results in a decrease in sheet resistance, which is beneficial to enhance the output current of HEMTs.

Figure 5 gives the impacts of NH_3/N_2 plasma on the output and transfer characteristics of AlGaN/GaN

HEMTs with AlN passivation. The NH_3/N_2 plasma pretreatment results in an increase in output current at gate voltage $V_G = 2\,V$ by about 20% for 1.2 μm devices and causes a negative shift of threshold voltage V_{th} by ~0.3 V due to an increase in n_s. Transfer sweep with drain voltage $V_D = 10\,V$ reveals little change in transconductance g_m except for the negative shift, as shown in the inset of Fig. 5(a), which indicates that remote plasma surface treatment has no effects on μ_n assuming gate capacitance unchanged.[16] Both the Hall measurement and g_m results prove that the remote NH_3/N_2 plasma surface treatment has no electrical damage on carriers[10] even with very high rf power. Figure 6 gives the impact of NH_3/N_2 plasma pre-treatment on the current slump of AlGaN/GaN HEMTs. Pulsed current with quiescent point at (0 V, 0 V), rather than dc current, was selected as the referenced state to eliminate the thermal effects. Even though AlN provides excellent surface passivation, the remote plasma can slightly improve the current collapse.

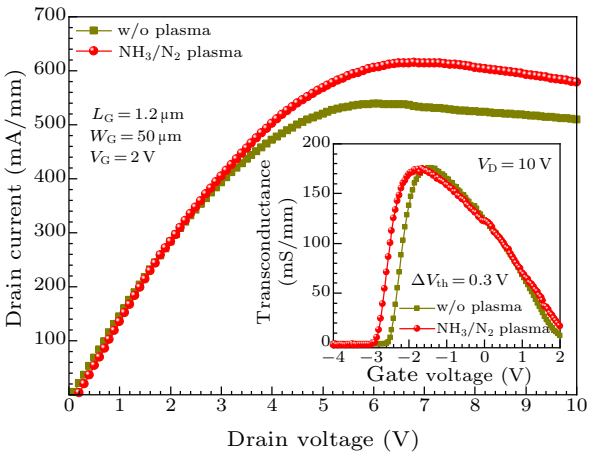

Fig. 5. Typical output current of AlN-passivated AlGaN/GaN HEMTs with and without NH_3/N_2 plasma pretreatment. The inset shows the compared transfer curves.

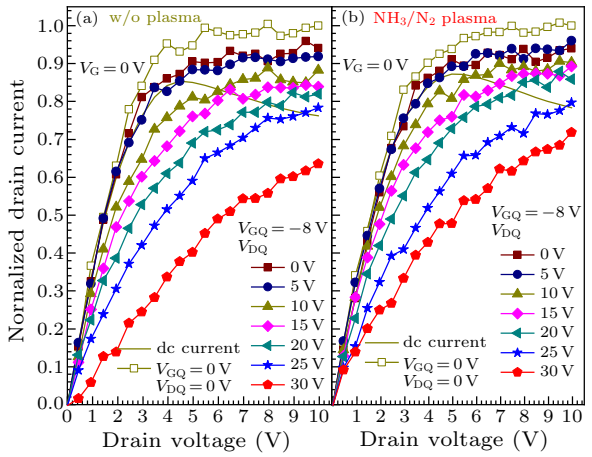

Fig. 6. Current slump of AlGaN/GaN HEMTs with AlN passivation (a) w/o and (b) with NH_3/N_2 plasma pretreatment.

Figure 7(a) shows the impacts of nitride-based plasma treatment on the Schottky contacts, where the Schottky barrier height $q\phi_b$ and ideal factor IF were extracted using the thermionic emission theory.[3,11] Improved IF and $q\phi_b$ are achieved by low-damage plasma treatment due to the reduced surface states, which also leads to a suppressed gate leakage current. The low-damage plasma treatment can increase the surface potential and then cause a decrease in n_s, which is contradictory to the Hall measurement results. This indicates that the variety of n_s was dominated by the re-distribution of surface donors.[20]

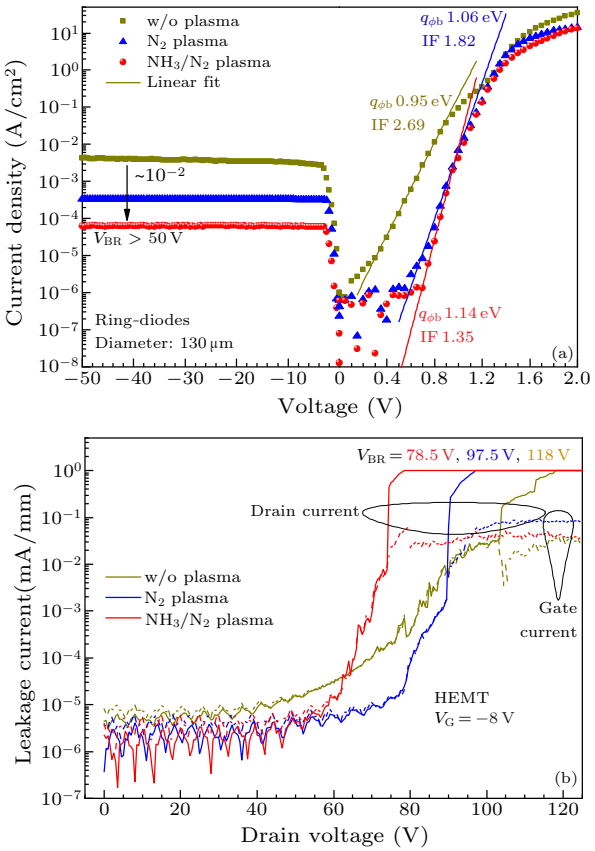

Fig. 7. Impacts of surface plasma treatment on the typical (a) Schottky contacts and (b) off-state breakdown characteristic of AlGaN/GaN HEMTs.

The three-terminal off-state leakage current curves are illustrated in Fig. 7(b). In low-field region with drain voltage below 60 V, the gate-drain leakage current is dominated by space charge limited current,[21] and plasma treatment results in a decrease in leakage current due to the reduced surface defects. This is consistent with the reverse leakage current of Schottky diodes. In high-field region with drain voltage above 70 V, the vertical field beneath the gate approaches the saturation electric field and tunneling current comes to be significant. The tunneling current is proportional to the product of n_s and μ_n as described in Ref. [21]. In high-field region, plasma treatment leads to an increase in $n_s \times \mu_n$ and leakage current, so the breakdown voltage, defined as the drain voltage where drain leakage current reached 1 mA/mm, demonstrates slight degeneration, which have been observed previously.[7] However, it is easy to improve the breakdown voltage by using insulator-gate structures, field plate, and by increasing the gate-drain distance.

The effects of nitride-based low-damage plasma treatment on the 2DEG and device characteristics of GaN-based HEMTs have been studied. Hall measurement and TLM analysis show that increasing 2DEG density and decreasing $R_{\rm sheet}$ are achieved using 200 W nitride-based remote plasma treatment, due to surface alteration. NH_3/N_2 plasma treatment causes little degeneration of $\mu_{\rm n}$ and device $g_{\rm m}$, and the increase in $n_{\rm s}$ leads to an increase in output current by about 20–30%. An increase in $R_{\rm c}$ by plasma treatment is also observed, because of the overestimate due to the depletion of N-vacancies near the edge of Ohmic areas. Nitride-based plasma treatment also results in the improved current slump, suppressed gate leakage current, and improved Schottky contact properties. In spite of the reduced breakdown voltage, NH_3/N_2 remote plasma treatment is a promising method for GaN-based HEMTs to modulate the surface conditions and channel properties.

References

[1] Ibbetson J P, Fini P T, Ness K D et al 2000 *Appl. Phys. Lett.* **77** 250
[2] Smorchkova I P, Elsass C R, Ibbetson J P et al 1999 *J. Appl. Phys.* **86** 4520
[3] Nakaji M, Egawa T, Ishikawa H et al 2002 *Jpn. J. Appl. Phys.* **41** L493
[4] Edwards A P, Mittereder J A, Binar S C et al 2005 *IEEE Electron Device Lett.* **26** 225
[5] Guhel Y, Boudart B, Vellas N et al 2005 *Solid-State Electron.* **49** 1589
[6] Meyer David J, Flemish J R and Redwing J M 2006 *Appl. Phys. Lett.* **89** 223523
[7] Meyer David J, Flemish J R and Redwing J M 2008 *Appl. Phys. Lett.* **92** 193505
[8] Kim J H, Choi H G, Ha M W et al 2010 *Jpn. J. Appl. Phys.* **49** 04DF05
[9] Romero M F, Jiménez A, Miguel Sánchez J et al 2008 *IEEE Electron Device Lett.* **29** 209
[10] Romero M F, Jiménez A, González-Posada F et al 2012 *IEEE Trans. Electron Devices* **59** 374
[11] Lee N H, Choi W, Lee M et al 2014 *CS MANTECH Conference* (Denver, Colorado, USA, 1–3 January 2014) p 245
[12] Her J C, Cho H J, Yoo C S et al 2010 *Jpn. J. Appl. Phys.* **49** 041002
[13] Liu X K, Low E K F, Pan J et al 2011 *Appl. Phys. Lett.* **99** 093504
[14] Huang S, Jiang Q, Yang S et al 2012 *IEEE Electron Device Lett.* **33** 516
[15] Yang S, Tang Z, Wong K Y et al 2013 *IEEE Electron Device Lett.* **34** 1497
[16] Zhu J J, Ma X H, Xie Y et al 2015 *IEEE Trans. Electron Devices* **62** 512
[17] Wang L, Mohammed F M and Adesida I 2008 *J. Appl. Phys.* **103** 093516
[18] Hierro A, Ringel S A, Hansen M et al 2000 *Appl. Phys. Lett.* **77** 1499
[19] Pearton S J, Zolper J C, Shul R J et al 1999 *J. Appl. Phys.* **86** 1
[20] Goyal N and Fjeldly T A 2014 *Appl. Phys. Lett.* **105** 033511
[21] Goswami A, Trew R J and Bilbro G L 2014 *IEEE Trans. Electron Devices* **61** 1014