Effects of the Perhydropolysilazane Spin-on-Dielectric Passivation Buffers on the Reliability of AlGaN/GaN HEMTs

Mustazar Iqbal, Pil-Seok Ko, and Sam-Dong Kim

***Abstract*—AlGaN/GaN high electron mobility transistors (HEMTs) are fabricated using a perhydropolysilazane spin-on-dielectric (SOD) buffered structure with the Si_3N_4 passivation, and the effects of SOD-buffers on high electric field degradation and high temperature stability are investigated. After the high-electric field stresses (high power-state and off-state) applied to the HEMTs, we observe significantly enhanced high-electric field reliability in terms of the DC current collapse (20 and 9 % for high-power state and off-state stress, respectively) from the SOD-buffered structure compared to that of the conventional passivation structure (44 and 18 % for each case). The SOD-buffered structure also shows an improved high temperature stability producing a lower saturation drain current reduction of 49 % than that of the conventional structure (60 %) at 300 ^{o}C. It is proposed that the reliability enhancement of SOD-buffered structure is due to the reduction in surface state density at the passivation interface and the suppressed electron trapping.**

***Index Terms*—Current collapse, high-temperature, reliability, SOD-buffer passivation.**

I. Introduction

AlGaN/GaN high-electron mobility transistors (HEMTs) are recently highlighted as a key device candidate for high frequency, high power, and high temperature applications due to their strengths in material properties such as high breakdown voltage and wide band-gap. A great deal of research progress has been reported in AlGaN/GaN HEMTs, especially, in high power applications [1] showing a significant development in the direction of product commercialization as well; however, they still need to overcome obstructions on the road by revealing themselves the reliable operation at high-electric field and high temperature stability [2].

GaN HEMTs are able to work at very high drain to source voltage because of their high breakdown voltages. However, due to the presence of high-electric field, the charged carriers can gain very high energy, consequently, activates the hot-electron phenomena (electron trapping in the surface) [3].

Manuscript received July 24, 2013; revised September 9, 2013. This work was supported by the Industrial Strategic technology development program (contract number 10038766) funded by the Ministry of Knowledge Economy (MKE, Korea) through ETRI and the Basic science research program (contract number 2012001298) through the National Research Foundation of Korea funded by the Ministry of Education, Science and Technology.

Mustazar Iqbal, Pil-Seok Ko, and Sam-Dong Kim are with the Division of Electronics and Electrical Engineering, Dongguk University, 3-26 Pildong Joonggu 100-715 Seoul, Korea (e-mail: engineer.mustazar@gmail.com, kops7665@naver.com, samdong@dongguk.edu).

One of the possible solutions to overcome this problem is to provide surface passivation. Passivation of the surface can improve the high-electric field reliability of GaN HEMT due to the minimized electron trappings at the surface states which depletes two-dimensional electron gas (2DEG) in the channel and induces the surface leakage current [4].

GaN high-power microwave devices also must function properly at high temperature without external cooling. In spite of their high band-gap property, they still suffer the drain current density reduction at elevated temperatures. For example, a 50 % decrease in saturation drain current density was reported from the AlGaN/GaN HEMTs on SiC [2] with increasing temperature equal to 250 ^{o}C. The drain current density reduction of ~60 % was also reported in conventional GaN channel HEMTs at 300 ^{o}C [5].

No extensive study has been reported to date on DC characteristics of the GaN HEMTs with SOD-buffered passivation structures at elevated temperature. In this work, we examine the effect of the thin SOD-buffer layer spun on the HEMT on hot-electron reliability and high temperature stability compared to the conventional PECVD Si_3N_4 passivation structure. A comprehensive DC characterization for the HEMTs of two different passivation structures is performed before and after the high power stress and temperature elevation up to 300 ^{o}C.

II. Experiments

Epitaxial structures used in this study (AlGaN/GaN HEMTs) were grown on Si (111) substrates by metal organic chemical vapor deposition. As shown in Fig. 1, the structure consists of buffer layers, unintentionally doped channel (3000-4000 nm), and AlGaN barrier layer with an Al composition of 25 % from the bottom. At top of the AlGaN layer, a GaN cap layer (1.25 nm) was finally grown to decrease the gate leakage current and ohmic contact resistance.

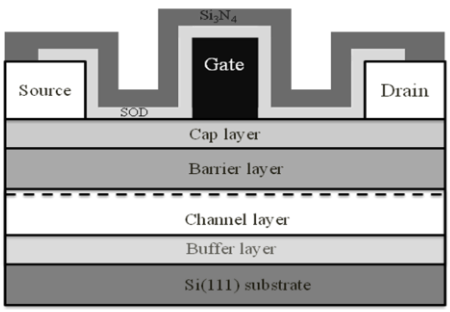

Fig. 1. Cross-section view of the HEMT with SOD-buffered passivation.

Cross sectional schematic of the SOD-buffered passivation structure is also shown in Fig. 1. To fabricate the HEMTs, mesa etching was first performed in order to isolate the active device areas by removing the 200 nm thickness of the neighboring areas in a reactive ion etching system using BCl_3 plus Cl_2 gases. The source and drain contacts were formed using electron-beam evaporation Ti/Al/Ni/Au layers (30/180/40/150 nm) annealing at 900 ^oC for 35 s in N_2 ambient. The Ni/Au (40/100 nm) Schottky gate electrodes were patterned by optical lithography with a gate-length of 2 µm, a gate width of 100 µm, and an extension of 2 µm from the source/drain to the central gate. In the case of buffered passivation structure, the SiO_x SOD-buffered films were coated after the gate metallization to protect the surface from plasma damage during the plasma-enhanced chemical vapor deposition Si_3N_4 deposition. For the SOD layers, a dibutyl ether solution of perhydropolysilazane (PHPS) was used as a silica source (1.0 wt%, UP chemical, Ceramable^{TM}) followed by prebake and curing at 400 ^oC using hot-plate for 3 min, and the final thickness was about 50 nm. Fig. 2 is showing the planner view of SOD-buffer fabricated AlGaN/GaN EHMT. The additional information for thin film characteristics of the coated PHPS SiO_x are described in our earlier report [6]. Finally, Si_3N_4 passivation layer with a thickness of 100 nm deposited at a RF power of 1 kW, and the pad-opening was finally performed.

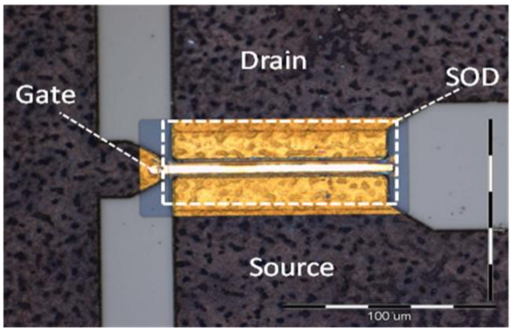

Fig. 2. Planner view of SOD-buffer AlGaN/GaN HEMT.

III. Off-State and High Power States

High electric field stress experiments were performed on the AlGaN/GaN HEMTs of SOD-buffered and conventional Si_3N_4 passivation structure. During the high power operation, both the hot-electron damage and the thermal effect due to self-heating can play roles in device degradation. However, the channel is open in off-state operation, the self-heating does not play any role in device degradation, instead of that, high-electric field present between the drain and gate region can degrade the device. With the aim to separate these possible source of degradation in high-electric field stress, we carry out two kinds of stress schemes of high-power step-stress (at V_{ds} = 0 to 40 V in steps of 5 V per 30 min and V_{gs} = 1 V) and off-state step-stress (at V_{ds} = 0 to 40 V in steps of 5 V per 30 min and V_{gs} = -6 V) with a computer controlled test arrangement connected to Agilent source measure unit (SMU) B2902A at room temperature in air. Stress experiments were carried out on 20 samples (10 samples for high-power state step-stress and 10 samples for off-state step-stress) in total.

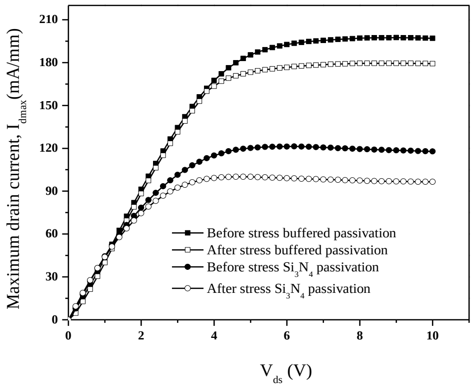

Fig. 3. I_{dmax} versus V_{ds} of the AlGaN/GaN HFMTs with SOD-buffered and conventional Si_3N_4 passivations before and after the off-state step-stress. Devices were stressed at V_{ds} = 5 to 40 V with a step of 5 V per 30 min and at V_{gs} = -6 V.

Fig. 3 illustrates the impact of 240-min off-state step-stress on I_{dmax} of two different passivation structures (SOD-buffered and Si_3N_4 passivations) for the AlGaN/GaN HEMTs. As shown in the measurements, the average I_{dmax} drop is more severe in the conventional Si_3N_4 passivation structure than that of the SOD-buffered structure; for example, the reductions in I_{dmax} (at V_{ds} = 10 V and V_{gs} = 1 V) produced by the off-state step-stresses were 18 and 9 % for the conventional and buffered structure, respectively. On the other hand, there was negligible threshold voltage (V_{th}) shift in both structures after the off-state step-stress.

Fig. 4 shows the normalized average I_{dmax} values measured before and after the high power-state step-stresses for 240 min in total. Degradation ratio in average I_{dmax} of the conventional passivation structure (~44 %) was almost two times greater than that of the buffered structure (~20 %). There were small positive shifts of the V_{th} in both cases, however they were negligible too. Degradations in I_{dmax} after the high-power state step-stress were higher those measured after the off-state step stress in both cases.

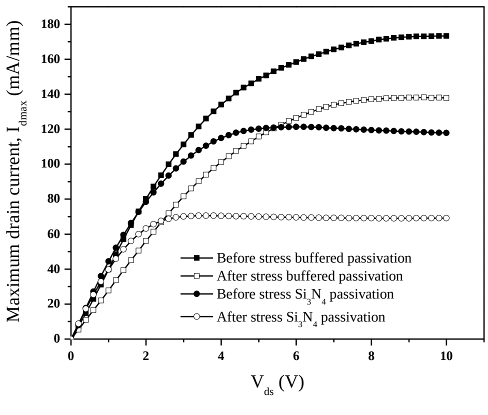

Fig. 4. I_{dmax} versus V_{ds} of the AlGaN/GaN HFMTs with SOD-buffered and conventional Si_3N_4 passivations before and after the high-power state step-stress. Devices were stressed at V_{ds} = 5 to 40 V with a step of 5 V per 30 min and at V_{gs} = 1 V.

Enhancement in high-electric field reliability of SOD-buffered structure devices can be attributed to the minimization in surface state density and trap centers. The electron trapping centers are attributed to the material imperfections or damaged layer produced by the device process; for example, plasma and thermal damage can produce nitrogen vacancies at the AlGaN layer surface [7] accounting for the current collapse. Even though the role of hot electrons in activating and/or converting the pre-existing carrier traps is not fully understood in hot carrier stress regime, our results propose that, during the stress stage, hot electrons from the channel can gain sufficient energy to overcome the energy barrier existing in the extrinsic region of the barrier/cap region and get trapped at the interface of the passivation. This leads to the change in electrostatics such that they deplete channel carrier concentration in the extrinsic drain, resulting in DC current collapse in the operation mode. Therefore, it can be postulated that our SOD-buffered passivation structure which is relatively free from plasma-damage provides a much lower density of trap centers than the conventional passivation structure; therefore, it can show a significant enhancement in DC reliability by minimizing the deleterious imperfections at the passivation interface known to be the most prominent trap centers.

IV. Temperature Stability

The AlGaN/GaN HEMT are anticipated for high temperature application due to its high band-gap energy. But as the temperature increased of AlGaN/GaN HEMT, its mobility and saturation velocity decreased. In order to examine the high temperature parameters stability, I_{dss}, $g_{m.max}$ and V_{th} of for the AlGaN/GaN HEMTs of two different passivation structures were measured in a temperature range of 25-300 ^{o}C, and 10 samples in total were measured for this experiment (5 from the SOD-buffered structure and 5 from the conventional passivation structure).

Fig. 5 shows the effect of temperature on I_{dss} (measured at V_{ds} = 10 V and V_{gs} = 0 V) normalized based on the reference values measured at 25 ^{o}C for two different passivation structures AlGaN/GaN HEMTs. Typical trends of current reduction with the temperature increase were observed in both structures. However, it is also obviously shown that the amount of current degradation of the buffered passivation structure is only ~49 % (σ = 1.5) and much lower than that of the conventional passivation structure (~60 %) at 300 ^{o}C.

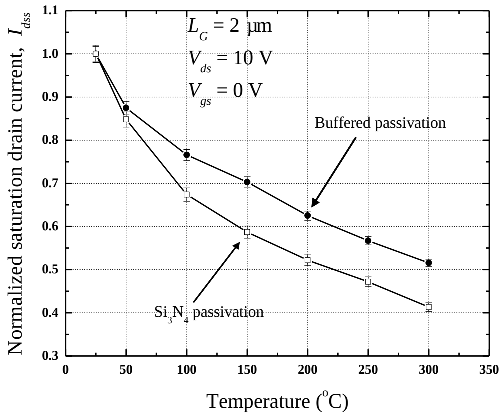

Fig. 5. Normalized saturation drain current as a function of temperature measured from the AlGaN/GaN HFMTs of SOD-buffered and conventional Si_3N_4 passivation structures.

Shown in Fig. 6 are the average $g_{m.max}$ normalized based on the reference values measured at 25 ^{o}C for two different passivation structures. The SOD-buffered structure also showed significantly enhanced high temperature stability in terms of $g_{m.max}$ reduction (~34 and ~44 % for the buffered and conventional passivation structure, respectively) at 300 ^{o}C. As shown in Fig. 7, the V_{th} shifts after the temperature elevation up to 300 ^{o}C were +0.25 and +0.28 V for the buffered and conventional passivation structure, respectively.

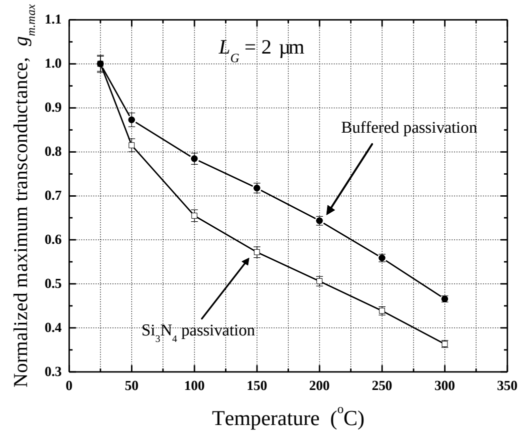

Fig. 6. Normalized maximum transconductance as a function of temperature measured from the AlGaN/GaN HFMTs of SOD-buffered and conventional Si_3N_4 passivation structures.

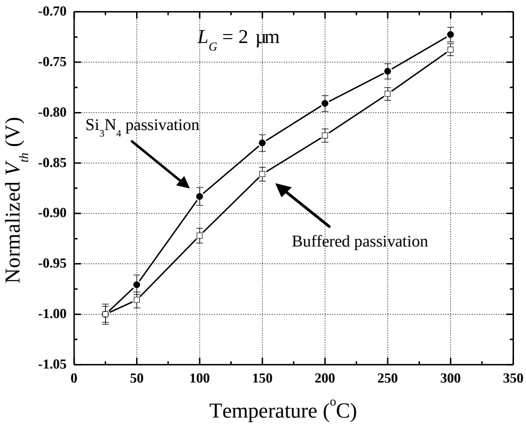

Fig. 7. Normalized threshold voltage as a function of temperature measured from the AlGaN/GaN HFMTs of SOD-buffered and conventional Si_3N_4 passivation structures.

V. Conclusions

In summary, a novel AlGaN-GaN HEMT structure of high temperature stability and high electric field reliability was successfully demonstrated by employing the SiO_x SOD-buffered passivation. After the off-state and high power states stresses, it was shown that the SOD-buffered HEMTs showed significantly smaller reduction in I_{dmax} compared to that of the conventional passivation structure. We also observed that the key device parameters of I_{dss}, $g_{m.max}$ and V_{th} measured from the SiO_x SOD-buffered passivation structure were more stable against the temperature elevation up to 300 ^{o}C than those of the conventional passivation structure. We propose that this enhancement was due to a much lower density of trap centers at the SOD-buffered passivation structure than that of the conventional passivation structure.

ACKNOWLEDGMENT

This work was supported by the Industrial Strategic technology development program (contract number 10038766) funded by the Ministry of Knowledge Economy (MKE, Korea) through ETRI and the Basic science research program (contract number 2012001298) through the National Research Foundation of Korea funded by the Ministry of Education, Science and Technology. The authors also would like to thank UP Chemical for supporting test materials.

REFERENCES

[1] M. Kanamura, T. Ohki, T. Kikkawa, K. Imanishi, K. Watanabe, and K. Joshin, "Recent progress in GaN HEMT for high-frequency and high-power applications," presented at the 2012 IEEE International Symposium on RFIT, Japan, November 21-23, 2012.

[2] N. Adachi, Y. Tateno, S. Mizuno, A. Kawano, J. Nikaido, and S. Sano, "High temperature operation of AlGaN/GaN HEMT," *Microwave Symposium Digest, 2005 IEEE MTT-S International, IEEE*, pp. 4, 2005.

[3] G. Meneghesso, F. Rampazzo, P. Kordos, G. Verzellesi, and E. Zanoni, "Current collapse and high-electric-field reliability of unpassivated GaN/AlGaN/GaN HEMTs," *IEEE Trans. Electron Devices*, vol. 53, pp. 2930-2941, December 2006.

[4] G. Wen-Ping, D. Huan-Tao, N. Jin-Yu, H. Yue, Z. Jin-Cheng, F. Qian, and M. Xiao-Hua, "High-electric-field-stress-induced degradation of SiN passivated AlGaN/GaN high electron mobility transistors," *Chin. Phys. B.*, vol. 18, pp. 1601, April 2009.

[5] M. Hatano, N. Kunishio, H. Chikaoka, J. Yamazaki, Z. B. Makhzani, N. Yafune, K. Sakuno, S. Hashimoto, K. Akita, and Y. Yamamoto, "Comparative high-temperature DC characterization of HEMTs with GaN and AlGaN channel layers," presented at CS Mantech Conference, Portland, U.S.A., pp. 101.

[6] P. S. Ko, M. Han, and S. D. Kim, "Perhydropolysilazane spin-on-dielectric passivation buffer layers for AlGaN/GaN high-electron mobility transistors," *Electron. Lett.*, vol. 48, pp. 1503-1504, November 2012.

[7] W. Saito, M. Kuraguchi, Y. Takada, K. Tsuda, I. Omura, and T. Ogura, "Influence of surface defect charge at AlGaN-GaN-HEMT upon Schottky gate leakage current and breakdown voltage," *IEEE Trans. Electron Devices*, vol. 52, pp. 159-164, February 2005.

Mustazar Iqbal was born in Gujrat, Pakistan. He received the B.S. degree in Electronics Engineering from BUITEMS, Pakistan, in 2010. He is currently pursuing the M.E. degree at the department of Electronics and Electrical Engineering, Dongguk University, Seoul, Korea. He was awarded a Study and Research at Dongguk University (SRD) with Full Scholarship, Korea. His research interests include semiconductor device design, fabrication, characterization and III-V semiconductor material.

Pil-Seok Ko was born in Gyeong Gi-Do, Korea. He received the B.S. degree in Electronics Engineering from the Dongguk University, Seoul, Korea in 2012. Also he is currently pursuing the M.E. degree at the department of Electronics and Electrical Engineering, Dongguk University, Seoul, Korea. His research interests include semiconductor fabrication and III-V semiconductor material.

Sam-Dong Kim received the B.E. and M.E. degrees from Seoul National University, Seoul, Korea, in 1983 and 1985, respectively, and the Ph.D. degree in material science and engineering from Stanford University, Stanford, CA, in 1992.

He was a senior research staff with the Hyundai Electronics Company Ltd., Icheon, Korea. He is currently a Professor with the Department of Electronic Engineering, Dongguk University, Seoul, Korea. His research interests have included millimeter-wave devices and novel semiconductor device processes.