Effect of Dielectric Thickness on Power Performance of AlGaN/GaN HEMTs

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***Abstract*—The effect of SiN$_x$ passivation thickness on the power performance of AlGaN/GaN high-electron-mobility transistors (HEMTs) has been studied. A model is proposed to explain the surface-state dispersion and passivation of AlGaN/GaN HEMTs. Based on this model, a multidielectic passivation method has been proposed and demonstrated to both provide lower dielectric capacitance and help remove dc–RF dispersion.**

***Index Terms*—Dielectric, gallium nitride, high-electron-mobility transistors (HEMTs), passivation, power, power-added efficiency (PAE).**

I. INTRODUCTION

OF GREAT interest in high-power RF applications are AlGaN/GaN high-electron-mobility transistors (HEMTs) due to their high electron mobility and high breakdown voltage. However, the power performance of AlGaN/GaN HEMTs had been limited by the dc–RF dispersion until the year of 2000, when a SiN$_X$ passivation method was proposed to suppress the surface traps [1], [2]. Since then, other dielectrics such as SiO$_2$, SiON [3], Sc$_2$O$_3$ [4], MgO/MgCaO [5], and AlN [6] have also been studied and have demonstrated the ability to decrease the dispersion. Among all the studied materials, SiN$_X$ is the most typical dielectric to mitigate RF dispersion, and all the state-of-the-art power performances of GaN HEMT from C-band to Ka-band have been achieved by using a thick SiN$_X$ passivation layer of more than 100 nm [7]–[9]. However, two problems need to be tackled when using a thick SiN$_X$ passivation layer in deep-submicrometer HEMTs. First, with a thick SiN$_X$ layer, a reliable gate recess and metallization process is challenging, particularly for gate length smaller than 100 nm. Second, due to the high dielectric constant of SiN$_X$, a thick SiN$_X$ passivation layer adds more fringe capacitance and significantly decreases the small signal gain [10], [11]. The state-of-the-art f_t and $f_{\max}$ were all reported from devices utilizing a thin SiN$_X$ [12] or without a SiN$_X$ passivation layer [13]. The power performance with reduced SiN$_X$ layer thickness is of great interest for GaN HEMT in Ka- or V-band applications.

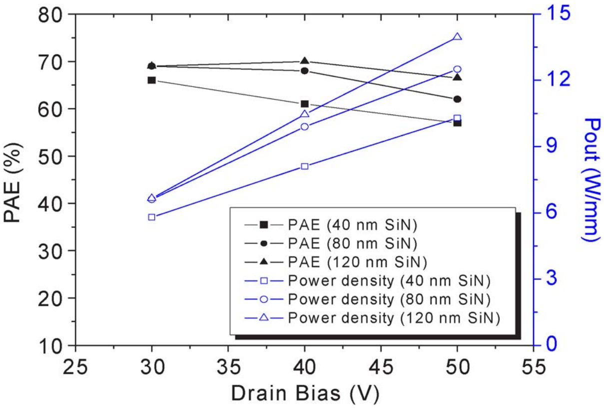

Fig. 1. Comparison of power density and PAE for different SiN$_X$ passivation layer thicknesses at different drain biases.

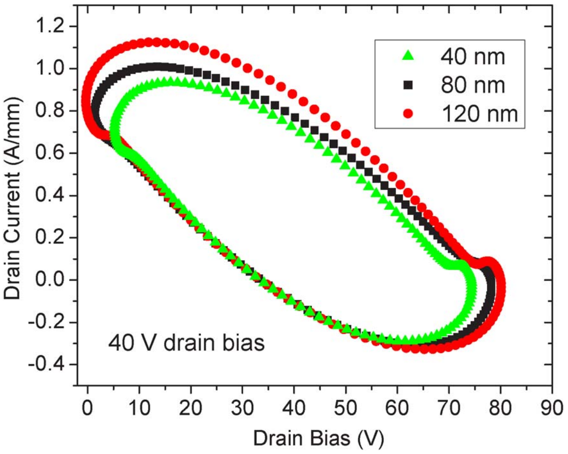

Fig. 2. Comparison of RF IV for AlGaN/GaN HEMTs with different SiN$_X$ thicknesses at 40-V drain bias.

In this letter, we studied the dependence of dc–RF dispersion on the SiN$_X$ passivation layer thickness and the drain bias. A model with air ionization was proposed, and a multidielectric passivation method was proposed based on the model. Initial results showed a very promising way to achieve both low dispersion and high power gain by using multidielectric passivation.

Manuscript received October 31, 2008; revised December 31, 2008. Current version published March 25, 2009. This work was supported by the ONR Millimeter-Wave Initiative for Nitride Electronics (MINE) project (with Dr. P. Maki and Dr. H. Dietrich as program managers). The review of this letter was arranged by Editor G. Meneghesso.

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Digital Object Identifier 10.1109/LED.2009.2012444

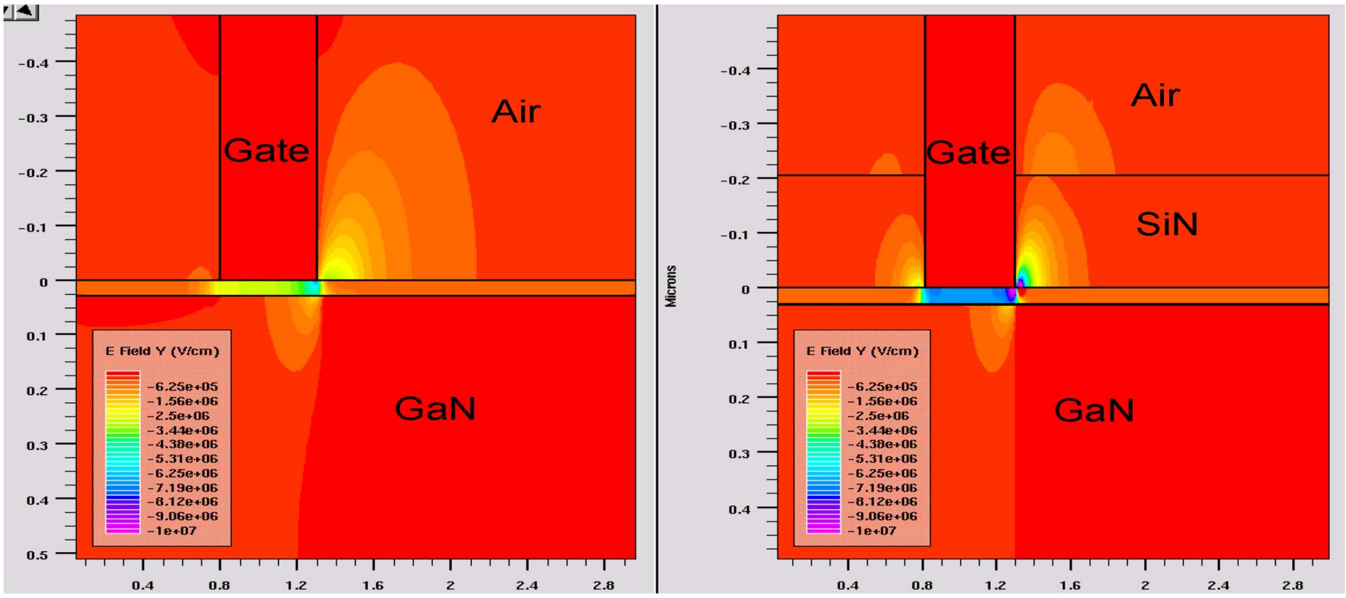

Fig. 3. Atlas simulation showing high electric fields up to 3 MV/cm in air and reduction in these electric fields (0.3 MV/cm) with introduction of SiN_X. The drain bias is 25 V.

II. SiN_X-THICKNESS-DEPENDENT DISPERSION

Three $\mathrm{Al}_{0.26}\mathrm{Ga}_{0.74}\mathrm{N}$/GaN HEMT wafers were grown on semi-insulating SiC substrates by MOCVD [14]. An annealed Ti/Al/Ni/Au stack was used as the ohmic contact. After the mesa was formed by the chlorine plasma etch, SiN_X was deposited by plasma-enhanced chemical vapor deposition on these three samples with different thicknesses of 40, 80, and 120 nm. Then, the $0.65 \times 150-\mu$m recessed slant-gate structure was fabricated, as described in [15].

CW large-signal measurement at 4 GHz was performed on these devices. As shown in Fig. 1, the transistor with a thick SiN_X passivation layer of 120 nm showed an excellent power density and power-added efficiency (PAE) up to 50 V. However, when the SiN_X thickness was thinner, a significant drop of the power density and PAE could be observed. Also, the dc–RF dispersion had a strong dependence on the drain bias. At 30-V drain bias, a SiN_X of 80 nm was enough to remove the dispersion, while a poor power performance showed up after 40-V drain bias. The maximum gamma of the load pull is 0.8511, giving a shunt resistance of 620 Ω. The maximum current of these transistors was approximately 150 mA, which meant that a 500–550-Ω load line was needed when a 40-V drain bias was used. Thus, the drop in PAE below 40 V was not due to the mismatch but due to an increase of dispersion. Another way to investigate the dispersion is by analyzing the dynamic load line. A microwave transition analyzer was connected to the load-pull system, and RF *IV* was measured [16], [17]. As shown in Fig. 2, when the SiN_X layer thickness was decreased, more knee-voltage walkout, less RF current and lower output power were observed. The difference was more obvious at a higher drain bias. This letter provides us a way to design our devices for different voltage applications. For ultrahigh-speed devices (Ka- to W-band) at the low drain bias, a thinner SiN_X passivation layer is preferred for the fringe capacitance consideration. However, for operations at lower frequency (S- to Ka-band) and at more than 40-V drain bias, a thick SiN_X passivation layer of more than 80 nm is preferred.

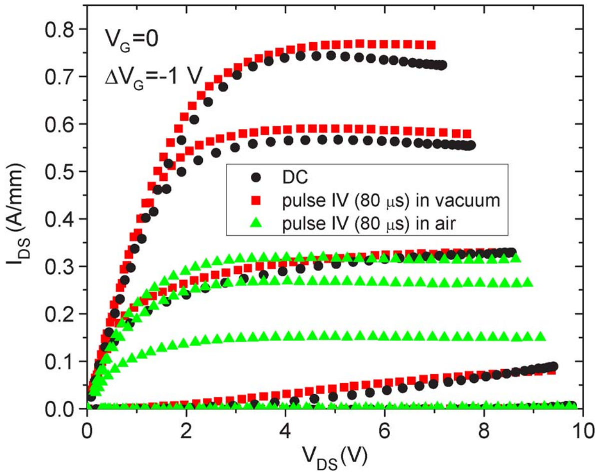

Fig. 4. Comparison of dc and pulsed *IV* of an AlGaN/GaN HEMT with a 2-nm SiN_X passivation layer in air and vacuum. A large dc–RF dispersion is seen in air, while in vacuum, there is no dispersion.

III. MODEL

In the previous study, the slow response of surface traps can make the electrons in the traps work as a virtual gate [2]. However, if the dispersion is only due to the surface, it should not be affected by the SiN_X thickness. A model taking into account the electric breakdown of the air above the gate–drain region is proposed, since there are very high electric fields due to the high polarization charge in AlGaN/GaN HEMTs. Our model showed that even when the AlGaN surface states were passivated, the air may have been exposed to high fields in the gate–drain region, causing ionization and charging of the surface (Fig. 3). The negative surface charges worked as an extended gate but were not able to respond fast enough in

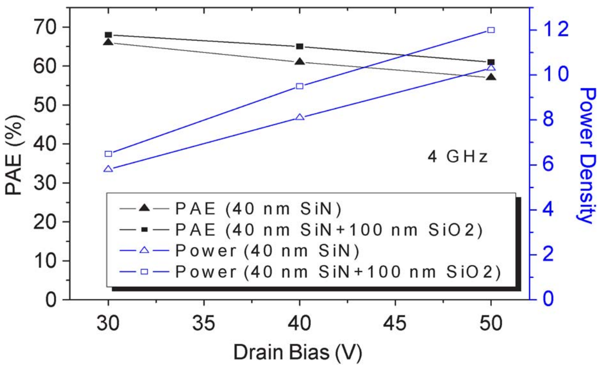

Fig. 5. Improvement of power density and PAE by SiO_2 passivation.

high-frequency operation conditions. This may have led to the dc–RF dispersion. Through the 2-D modeling, the electric field was decreased with a certain thick SiN_X layer at a given drain bias, so that the air breakdown could be prevented.

To verify the model, pulse–IV measurement was carried on a controlled sample with a 2-nm-SiN_X passivation layer and a 150-nm gate. The transistor was biased at a drain voltage of 10 V with a 32-Ω load line, and the gate was swept from -4 to 0 V in an 80-μs pulse. As shown in Fig. 4, a large dc–RF dispersion could be seen in the off-to-on gate pulse measurement in air. When it was measured in a vacuum environment with a pressure of 1×10^{-3} torr, no dispersion could be observed for the same device. The results suggested that our model might be correct.

IV. MULTIDIELECTRIC

Based on our model, dielectrics other than SiN_X are also expected to eliminate dispersion if the AlGaN surface states are passivated and air ionization is prevented. We propose a multidielectric layer stack, which consists of a bottom thin SiN_X layer to passivate the surface and a top layer for the electric field reduction. To reduce the fringe capacitance, a low-dielectric-constant material such as SiO_2 or BCB can be used. In the work, a 100-nm SiO_2 was deposited on 40-nm SiN_X passivated devices by PECVD, and power measurement was performed at 4 GHz. From Fig. 5, an increase of power density and PAE was observed at all drain biases. The dynamic load-line analysis also showed a decrease of knee-voltage walkout and an increase of RF current. It was probably due to a decrease of electric field in air due to the thick SiO_2 passivation layer, which caused less air ionization. The power performance of the SiN_X/SiO_2-passivated transistors was still slightly worse than that of the 120-nm SiN_X-passivated ones, possibly due to the interface traps between SiN_X and SiO_2. A more effective surface pretreatment before the SiO_2 deposition or depositing SiO_2 without exposing SiN_X to air might be ways for solving this problem.

V. CONCLUSION

In summary, we found that the dc–RF dispersion was not only related to the surface passivation but also depends on the SiN_X passivation layer thickness. A model with air ionization was proposed to explain it. Based on this model, a multidielectric passivation stack was used and shown to decrease the dispersion while providing less fringe capacitance. It provides a key way for AlGaN/GaN HEMT to solve power gain and dispersion at the same time.

REFERENCES

[1] B. M. Green, K. K. Chu, E. M. Chumbes, J. A. Smart, J. R. Shealy, and L. F. Eastman, "The effect of surface passivation on the microwave characteristics of undoped AlGaN/GaN HEMTs," *IEEE Electron Device Lett.*, vol. 21, no. 6, pp. 268–270, Jun. 2000.

[2] R. Vetury, N. Q. Zhang, S. Keller, and U. K. Mishra, "The impact of surface states on the DC and RF characteristics of AlGaN/GaN HFETs," *IEEE Trans. Electron Devices*, vol. 48, no. 3, pp. 560–566, Mar. 2001.

[3] S. Arulkumaran, T. Egawa, H. Ishikawa, T. Jimbo, and Y. Sano, "Surface passivation effects on AlGaN/GaN high-electron-mobility transistors with SiO_2, Si_3N_4 and silicon oxynitride," *Appl. Phys. Lett.*, vol. 84, no. 4, pp. 613–615, Jan. 2004.

[4] N. A. Moser, J. K. Gillespie, G. D. Via, A. Crespo, M. J. Yannuzzi, G. H. Jessen, R. C. Fitch, B. Luo, F. Ren, B. P. Gila, A. H. Onstine, C. R. Abernathy, and S. J. Pearton, "Effects of surface treatments on isolation currents in AlGaN/GaN high-electron-mobility transistors," *Appl. Phys. Lett.*, vol. 83, no. 20, pp. 4178–4180, Nov. 2003.

[5] B. P. Gila, M. Hlad, A. H. Onstine, R. Frazier, G. T. Thaler, A. Herrero, E. Lambers, C. R. Abernathy, S. J. Pearton, T. Anderson, S. Jang, F. Ren, N. Moser, R. C. Fitch, and M. Freund, "Improved oxide passivation of AlGaN/GaN high electron mobility transistors," *Appl. Phys. Lett.*, vol. 87, no. 16, p. 163 503, Oct. 2005.

[6] J. Hwang, W. J. Schaff, B. N. Green, H. Cha, and L. Eastman, "Effect of a molecular beam epitaxy grown AlN passivation layer on AlGaN/GaN heterojunction field effect transistors," *Solid State Electron.*, vol. 48, no. 2, pp. 363–366, Feb. 2004.

[7] Y. F. Wu, M. Moore, A. Saxler, T. Wisleder, and P. Parikh, "40-W/mm double field-plated GaN HEMTs," in *Proc. 64th Device Res. Conf.*, 2006, pp. 151–152.

[8] Y. Pei, R. Chu, L. Shen, N. A. Fichtenbaum, Z. Chen, D. Brown, S. Keller, S. P. Denbaars, and U. K. Mishra, "Recessed slant gate AlGaN/GaN high electron mobility transistors with 20.9 W/mm at 10 GHz," *Jpn. J. Appl. Phys.*, vol. 46, no. 45, pp. L1 087–L1 089, 2007.

[9] Y. F. Wu, M. Moore, A. Abrahamsen, M. J. Mitos, P. Parikh, S. Heikman, and A. Burk, "High voltage millimeter-wave GaN HEMTs with 13.7 W/mm power density," in *IEDM Tech. Dig.*, 2007, pp. 405–407.

[10] T. Palacios, A. Chakraborty, S. Heikman, S. Keller, S. P. DenBaars, and U. K. Mishra, "AlGaN/GaN high electron mobility transistors with InGaN back-barriers," *IEEE Electron Device Lett.*, vol. 27, no. 1, pp. 13–15, Jan. 2006.

[11] Y. Pei, M. Higashiwaki, U. K. Mishra, and S. Rajan, "*Gallium Nitride Transistor in a Vacuum Package,*" Provisional patent application, Docket 30794.286-US-P1.

[12] M. Higashiwaki, T. Mimura, and T. Matsui, "AlGaN/GaN heterostructure field-effect transistor on 4H-SiC substrates with current-gain cutoff frequency of 190 GHz," *Appl. Phys. Exp.*, vol. 1, no. 2, p. 021 103, 2008.

[13] T. Palacios, E. Snow, Y. Pei, A. Chakraborty, S. Keller, S. P. DenBaars, and U. K. Mishra, "Ge-spacer technology in AlGaN/GaN HEMTs for mm-wave applications," in IEDM Tech. Dig., 2005, p. 32.7.

[14] Z. Chen, Y. Pei, S. Newman, R. Chu, D. Brown, R. Chung, S. Keller, S. P. Denbaars, S. Nakamura, and U. K. Mishra, *Growth of AlGaN/GaN heterojunction field effect transistor on semi-insulating GaN facilitated by an AlGaN inserlayer*. submitted to APL for publication.

[15] Y. Pei, R. Chu, L. Shen, N. A. Fichtenbaum, Z. Chen, D. Brown, S. Keller, S. P. Denbaars, and U. K. Mishra, "Effect of Al composition and gate recess on power performance of AlGaN/GaN high-electron mobility transistors," *IEEE Electron Device Lett.*, vol. 29, no. 4, pp. 300–302, Apr. 2008.

[16] B. M. Green, V. S. Kaper, V. Tilak, J. R. Shealy, and L. F. Eastman, "Dynamic load line analysis of AlGaN/GaN HEMTs," in *Proc. High Performance Devices, Lester Conf.*, 2002, pp. 443–452.

[17] S. Rajan, A. Chakraborty, C. Poblenz, P. Waltereit, J. S. Speck, and U. K. Mishra, "MBE-grown AlGaN/GaN HEMTs on SiC," *Int. J. High Speed Electron. Syst.*, vol. 14, no. 3, pp. 732–737, 2004.