Simulation of Breakdown Voltage Enhancement in AlGaN/GaN HEMTs with Double Passivation Layers

K. Horio and H. Hanawa

Faculty of Systems Engineering, Shibaura Institute of Technology
307 Fukasaku, Saitama 337-8570, Japan, horio@sic.shibaura-it.ac.jp

ABSTRACT

Two-dimensional analysis of off-state drain current-drain voltage characteristics in AlGaN/GaN HEMTs is performed; where two cases with a single passivation layer (SiN) and double passivation layers (thin SiN and high-*k* dielectric) are compared. It is shown that in the case of double passivation layers, the breakdown voltage is enhanced significantly when comparing at the same insulator thickness, because the electric field at the drain edge of the gate is reduced. It is also shown that in the case of double passivation layers, the breakdown voltage becomes higher when the relative permittivity of the second passivation layer becomes higher.

Keywords: GaN HEMT, breakdown voltage, double passivation layer, high-*k* dielectric

1 INTRODUCTION

Recently, AlGaN/GaN HEMTs are receiving great attention because of their applications to high-power microwave devices and high-power switching devices [1, 2]. It is well known that the introduction of field plate improves the power performance of AlGaN/GaN HEMTs [3-5]. This is because the field plate can reduce so-called current collapse [6, 7] and also enhance the off-state breakdown voltage [8-10]. The enhancement of the breakdown voltage occurs because the electric field around the drain edge of the gate is reduced by introducing the field plate. However, the field plate may increase a parasitic capacitance, leading to the degradation of the high frequency performance.

In order to improve the breakdown voltage, introducing a passivation layer with high permittivity can also be considered [11-13]. In fact, the introduction of a high-*k* layer may smooth electric field profiles between the gate and the drain. The high-*k* dielectric is studied as a gate insulator in GaN-based MISHEMTs as well as Si MOSFETs. For example, HfO_2 (relative permittivity: $\varepsilon_r \sim 20$), La_2O_3 ($\varepsilon_r \sim 27$) , $LaLuO_3$ ($\varepsilon_r \sim 28$) and TiO_2 ($\varepsilon_r \sim 55$) etc. are studied in AlGaN/GaN MISHEMTs [14-16]. In previous works [12, 13], we considered the high-*k* dielectric only as a passivation layer and calculated off-state breakdown characteristics of AlGaN/GaN HEMTs as a parameter of passivation layer's relative permittivity ε_r, and showed that the breakdown voltage was enhanced when ε_r was high. But, when the high-k materials are used, the structure may have high interface-state densities which leads to the degradation of device performance due to the trapping effects. Therefore, in this study, we propose a structure with double passivation layers where the first passivation layer is a thin SIN layer having low interface-state densities and the second passivation layer is a high-*k* dielectric, and study how the breakdown voltage is enhanced.

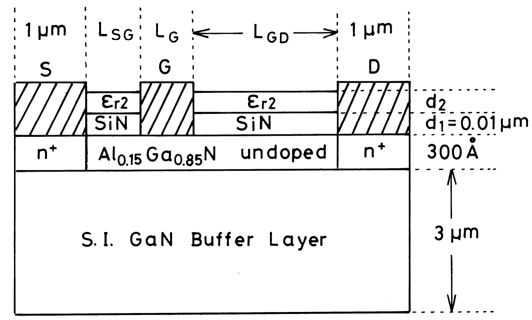

Figure 1: Device structures simulated in this study.

2 PHYSICAL MODELS

Fig.1 shows a device structure analyzed in this study. The gate length L_G is 0.3 μm and the gate-to-drain distance L_{GD} is 1.5 μm. The thickness of first passivation layer (SiN) d_1 is 0.01 μm and the relative permittivity is 7. The thickness of second passivation layer d_2 and its relative permittivity ε_{r2} are varied as parameters. Polarization charges of 10^{13} cm^{-2} are considered at the heterojunction interface. It is assumed that surface polarization charges are compensated by surface-state charges [8, 10]. In a semi-insulating buffer layer, we consider a shallow donor, a deep donor, and a deep acceptor [17-19]. As an energy level of the deep acceptor, we consider $E_C - 2.85$ eV ($E_V + 0.6$ eV). For impurity compensation, we consider the deep donor whose energy level is $E_C - 0.5$ eV. The deep-acceptor density N_{DA} is set rather high of 10^{17} cm^{-3}. A study [20] indicates that to reduce short-channel effects, an acceptor density in a buffer layer should be higher than 10^{17} cm^{-3}.

Basic equations to be solved are Poisson's equation including ionized deep-level terms and continuity equations for electrons and holes including a carrier generation rate by impact ionization and carrier loss rates via the deep levels[10, 21-23]. These equations are expressed as follows.

1) Poisson's equation

$$\nabla \bullet (\varepsilon \nabla \psi) = -q(p - n + N_{\mathrm{Di}} + N_{\mathrm{DD}}^{+} - N_{\mathrm{DA}}^{-}) \qquad (1)$$

2) Continuity equations for electrons and holes

$$\nabla \bullet J_n = -qG + q(R_{\mathrm{DD}} + R_{\mathrm{DA}}) \qquad (2)$$

$$\nabla \bullet J_p = qG - q(R_{\mathrm{DD}} + R_{\mathrm{DA}}) \qquad (3)$$

where N_{DD}^{+} and N_{DA}^{-} are the ionized deep-donor and deep-acceptor densities, respectively. R_{DD} and R_{DA} represent carrier recombination rates via the deep donors and the deep acceptors, respectively. G is a carrier generation rate by impact ionization, and given by

$$G = (\alpha_n |J_n| + \alpha_p |J_p|)/q \qquad (4)$$

where α_n and α_p are ionization rates for electrons and holes, respectively, and expressed as

$$\alpha_n = A_n \exp(-B_n / |E|) \qquad (5)$$

$$\alpha_p = A_p \exp(-B_p / |E|) \qquad (6)$$

where E is the electric field. A_n, B_n, A_p, and B_p are deduced from [24]. The above basic equations are put into discrete forms and solved numerically.

3 CALCULATED RESULTS AND DISCUSSIONS

Figs.2(a) and (b) show a comparison of calculated drain current I_D – drain voltage V_D curves of AlGaN/GaN HEMTs as a parameter of d_2 between the two cases with (a) a single passivation layer (SiN; ε_{r2} = 7) and (b) double passivation layers having a high-*k* dielectric (ε_{r2} = 20). The gate voltage is − 8 V, which corresponds to an off state. In the case with a single passivation layer of SiN (Fig.2(a)), I_D increases suddenly due to impact ionization of carriers, showing breakdown. In the case with double passivation layers (Fig.2(b)), I_D increases suddenly when d_2 is relatively thin but when d_2 becomes thick, I_D increases gradually and reaches a critical value of I_D (1 mA/mm) before the abrupt increase in I_D. Fig.3 shows the breakdown voltage V_{br} as a function of the thickness of second passivation layer d_2. Here, V_{br} is defined as a drain voltage where I_D becomes 1 mA/mm. It is clearly seen that V_{br} is higher for the double passivation layers (ε_{r2} = 20), particularly in the cases of thicker d_2. This is because the electric field at the drain edge of the gate is reduced in the case with double passivation layers having a high-*k* dielectric, as described below.

Fig.4 shows a comparison of electric field profiles along the AlGaN/GaN interface between the two cases with (a) single passivation layer (SiN; ε_{r2} = 7) and (b) double passivation layers having a high-*k* dielectric (ε_{r2} = 20). Here, d_2 = 0.19 μm. In the case with a single passivation layer (SiN; ε_{r2} = 7), an increase in V_D is almost applied along the drain edge of the gate, resulting in the abrupt increase in I_D around V_D = 103 V. In the case with double passivation layers having a high-*k* dielectric (ε_{r2} = 20), the electric field at the drain edge of the gate is reduced, and it is not so high at V_D = 100 V. As V_D increases, the electric field between the gate and the drain increases, and the electric field near the drain begins to become high around V_D = 200 V. Then, the electric field at the drain edge of the gate also becomes rather high at V_D = 288 V, which corresponds to the breakdown voltage. Therefore, the breakdown voltage becomes higher in the case with double passivation layers having a high-*k* dielectric.

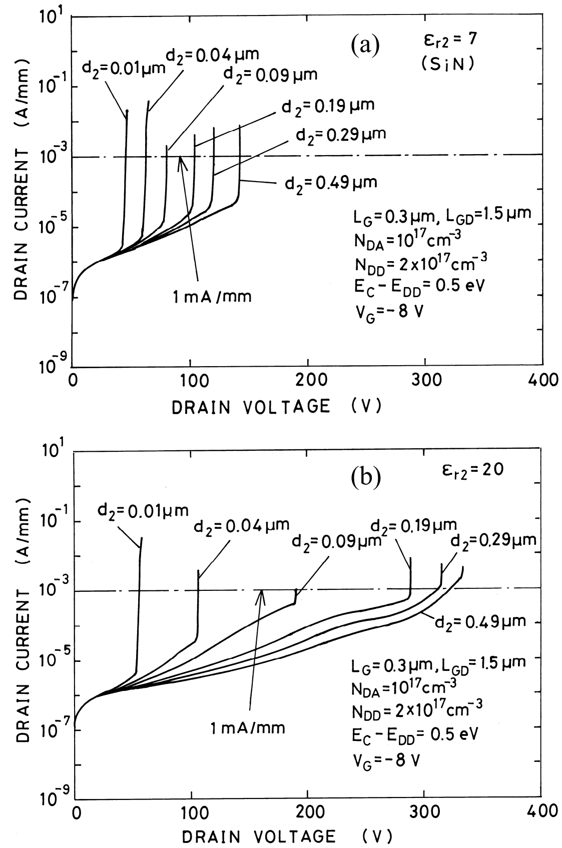

Figure 2: Calculated I_D-V_D curves as a parameter of d_2. V_G = – 8 V. (a) ε_{r2} = 7, (b) ε_{r2} = 20.

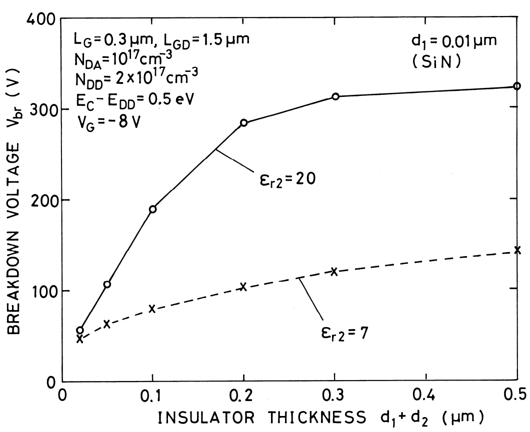

Figure 3: Comparison of breakdown voltage V_{br} versus insulator thickness curves between ε_{r2} = 7 and 20

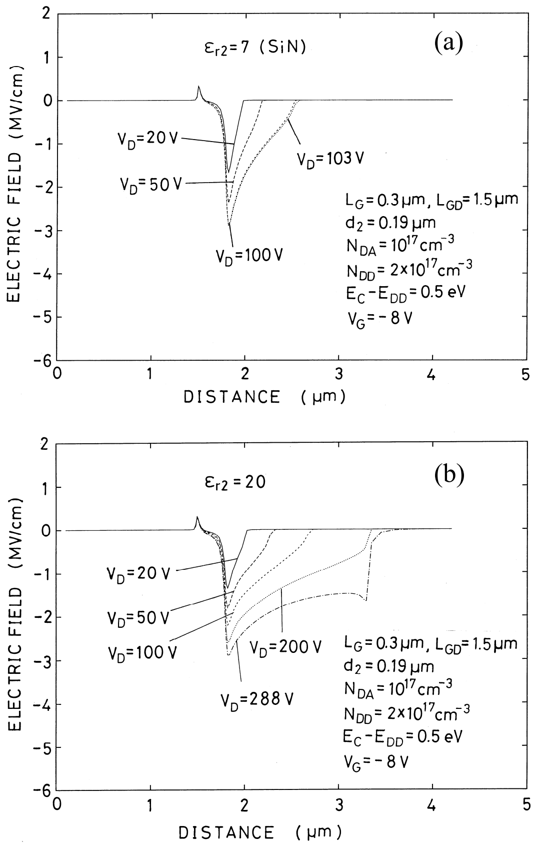

Figure 4: Electric field profiles along the heterojunction interface. (a) ε_{r2} = 7, (b) ε_{r2} = 20.

Fig.5 shows calculated I_D-V_D curves of AlGaN/GaN HEMTs with double passivation layers as a parameter of relative permittivity of second passivation layer ε_{r2}. Here, d_2 = 0.09 μm ($d_1 + d_2$ = 1 μm). When ε_{r2} is low, the drain current increases suddenly due to impact ionization of carriers, as in the case of single passivation layer. But, as ε_{r2} becomes high (> 30), the drain current increases gradually and reaches the current level of breakdown (1 mA/mm). Fig.6 shows the breakdown voltage V_{br} versus ε_{r2} curve. When ε_{r2} becomes high, the breakdown voltage becomes higher than 300 V, as in the case of ε_{r2} = 20 and thicker d_2 shown before (Fig.3). V_{br} = 300 V corresponds to an average electric field of 2 MV/cm between the gate and the drain.

4 CONCLUSION

We have made a two-dimensional numerical analysis of off-state breakdown characteristics in AlGaN/GaN HEMTs, where two cases with a single passivation layer (SiN) and double passivation layers (thin SiN and high-*k* dielectric) are considered. It has been shown that in the case with double passivation layers having a high-*k* dielectric, the breakdown voltage become much higher at the same insulator thickness, because the electric field at the drain

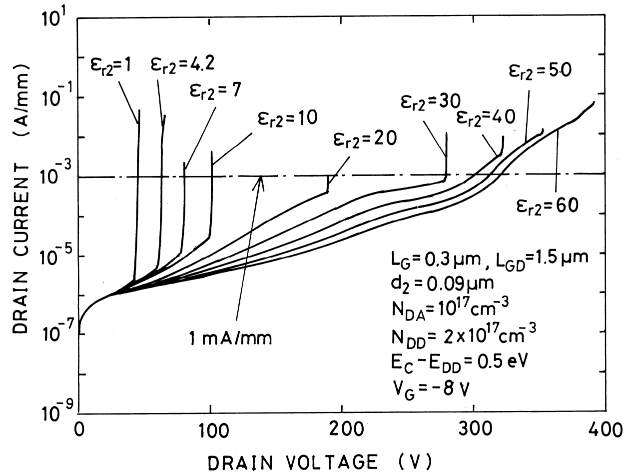

Figure 5: Comparison of breakdown voltage V_{br} versus insulator thickness curves between ε_{r2} = 7 and 20

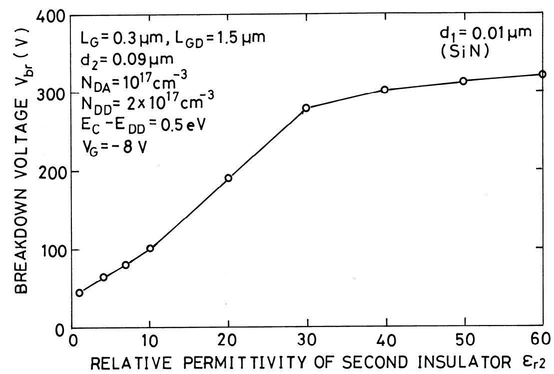

Figure 6: Breakdown voltage V_{br} versus ε_{r2} curve. d_2 = 0.09 μm.

edge of the gate is reduced. It has also been shown that in the case of double passivation layers, the breakdown voltage becomes higher when the relative permittivity of the second passivation layer becomes higher.

Finally, it should be mentioned that to study how the high-*k* passivation layer affects the so-called current collapse in AlGaN/GaN HEMTs is an important task yet to be done [25].

REFERENCES

[1] U. K. Mishra, L. Shen, T. E. Kazior, and Y.-F. Wu, “GaN-based RF power devices and amplifiers”, Proc. IEEE, vol.96, pp.287-305, 2008.

[2] N. Ikeda, Y. Niiyama, H. Kambayashi, Y. Sato, T. Nomura, S. Kato, and S. Yoshida, “GaN power transistors on Si substrates for switching applications”, Proc. IEEE, vol.98, pp.1151-1161, 2010.

[3] Y. Ando, Y. Okamoto, H. Miyamoto, T. Nakayama, T. Inoue, and M. Kuzuhara, “10-W/mm

AlGaN/GaN HFET with a field modulating plate," IEEE Electron Device Lett., vol. 24, pp. 289–291, 2003.
[4] Y.-F. Wu, A. Saxler, M. Moore, R. P. Smith, S. Sheppard, P. M. Chavarkar, T. Wisleder, U. K. Mishra, and P. Parikh, "30-W/mm GaN HEMTs by field plate optimization", IEEE Electron Device Lett., vol.25, pp.117-119, 2004.
[5] Y. Hao, L. Yang, X. Ma, J. Ma, M. Cao, C. Pan, C. Wang, and I. Zhang, "High-performance microwave gate-recessed AlGaN/AlN/GaN MOS-HEMT with 73% power-added efficiency", IEEE Electron Device Lett., vol.32, pp.626-628, 2011.
[6] A. Brannick, N. A. Zakhleniuk, B. K. Ridley, J. R. Shealy, W. J. Schaff, and L. F. Eastman, "Influence of field plate on the transient operation of the AlGaN/GaN HEMT", IEEE Electron Device Lett., vol.30, pp.436-438, 2009.
[7] K. Horio, A. Nakajima, and K. Itagaki, "Analysis of field-plate effects on buffer-related lag phenomena and current collapse in GaN MESFETs and AlGaN/GaN HEMTs", Semicond. Sci. Technol., vol.24, pp.085022-1–085022-7, 2009.
[8] S. Karmalkar and U. K. Mishra, "Enhancement of breakdown voltage in AlGaN/GaN high electron mobility transistors using a field plate", IEEE Trans. Electron Devices, vol.48, pp.1515-1521, 2001.
[9] E. Bahat-Treidel, O. Hilt, F. Brunner, V. Sidorov, J. Würfl, and G. Tränkle, "AlGaN/GaN/AlGaN DH-HEMTs breakdown voltage enhancement using multiple gating field plates (MGFPs)", IEEE Trans. Electron Devices, vol.57, pp.1208-1216, 2010.
[10] H. Onodera and K. Horio, "Analysis of buffer-impurity and field-plate effects on breakdown characteristics in small sized AlGaN/GaN high electron mobility transistors", Semicond. Sci. Technol., vol.27, pp.085016-1–085016-6, 2012.
[11] Q. Luo and Q. Yu, "Electric field modulation by introducing a *HK* dielectric film of tens of nanometers in AlGaN/GaN HEMT", *Nanosci. Nanotechnol. Lett*., vol.4, pp.936-939, 2012.
[12] H. Hanawa and K. Horio, "Increase in breakdown voltage of AlGaN/GaN HEMTs with a high-*k* dielectric layer", Phys. Status Solidi A, vol.211, pp.784-787, 2014.
[13] H. Hanawa, H. Onodera, A. Nakajima, and K. Horio, "Numerical analysis of breakdown voltage enhancement in AlGaN/GaN HEMTs with a high-*k* passivation layer", IEEE Trans. Electron Devices, vol.61, pp.769-775, 2014.
[14] C. Liu, E. F. Chor, and L. S. Tan, "Enhanced device performance of AlGaN/GaN HEMTs using HfO_2 high-*k* dielectric for surface passivation and gate oxide", Semicond. Sci. Technol., vol.22, pp.522-527 , 2007.
[15] S. Yang, S.Huang, H. Chen, C. Zhou, Q. Zhou, M. Schnee, Q. Zhao, J. Schubert, and K. J. Chen, "AlGaN/GaN MISHEMTs with high-*k* $LaLuO_3$ gate dielectric", IEEE Electron Device Lett., vol.33, pp.979-981, 2012.
[16] C.-S. Lee, W.-C. Hsu, B.-Y. Chpu, H.-Y. Liu, C.-L. Yang, W.-C. Sun, S.-Y. Wei, S.-M. Yu, and C.-L. Wu, "Investigation of TiO_2-AlGaN/GaN/Si-passivated HFETs and MOS-HFETs using ultrasonic spray pyrolysis deposition", IEEE Trans. Electron Devoces, vol.62, pp.1460-1466, 2015.
[17] K. Horio, K. Yonemoto, H. Takayanagi, and H. Nakano, "Physics-based simulation of buffer-trapping effects on slow current transients and current collapse in GaN field effect transistors", J. Appl. Phys., vol.98, pp.124502-1–124502-7, 2005.
[18] K. Horio and A. Nakajima, "Physical mechanism of buffer-related current transients and current slump in AlGaN/GaN high electron mobility transistors", Jpn. J. Appl. Phys., vol.47, pp.3428-3433, 2008.
[19] K. Horio, H. Onodera, and A. Nakajima, "Analysis of backside-electrode and gate-field-plate effects on buffer-related current collapse in AlGaN/GaN high electron mobility transistors", J. Appl. Phys., vol.109, pp.114508-1–114508-7, 2011.
[20] M. J. Uren, K. J. Nash, R. S. Balmer, T. Martin, E. Morvan, N. Caillas, S. L. Delage, D. Ducatteau, B. Grimbert, and J. C. De Jaeger, "Punch-through in short-channel AlGaN/GaN HFETs", IEEE Trans. Electron Devices, vol.53, pp.395-398, 2006.
[21] K. Horio and K. Satoh, "Two-dimensional analysis of substrate-related kink phenomena in GaAs MESFET's", IEEE Trans. Electron Devices, vol.41, pp.2256-2261, 1994.
[22] K. Horio and A. Wakabayashi, "Numerical analysis of surface-state effects on kink phenomena of GaAs MESFETs", IEEE Trans. Electron Devices, vol.47, pp.2270-2276, 2000.
[23] Y. Mitani, D. Kasai and K. Horio, "Analysis of surface-state and impact-ionization effects on breakdown characteristics and gate-lag phenomena in narrowly-recessed-gate GaAs FETs", IEEE Trans. Electron Devices, vol.50, pp.285-291, 2003.
[24] C. Bulutay, "Electron initiated impact ionization in AlGaN alloys", Semicond. Sci. Technol., vol.17, pp.59-62, 2002.
[25] Y. Satoh, H. Hanawa, A. Nakajima, and K. Horio, "Analysis of high-*k* passivation-layer effects on buffer-related breakdown and current collapse in AlGaN/GaN HEMTs", Jpn J. Appl. Phys., vol.54, pp.031002-1–031002-5, 2015.