Effects of Buffer Acceptors on Breakdown Voltages of AlGaN/GaN HEMTs with a High-k Passivation Layer

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ABSTRACT

We analyze AlGaN/GaN HEMTs with a buffer layer where a deep acceptor above the midgap is considered, and studied how the off-state breakdown voltage is influenced by introducing a high-k passivation layer. As a result, it is shown that the breakdown voltage improves as in a case with a deep donor whose energy level is set equal to the acceptor's energy level, and in this case the breakdown voltage becomes a little higher in the region where the relative permittivity of the passivation layer is high. It is also shown that when the deep-acceptor's energy level is deeper, the breakdown voltage becomes higher in the high-*k* region because the buffer leakage current becomes smaller.

Keywords: GaN HEMT, breakdown voltage, deep acceptor, high-*k* passivation layer,, two-dimensional analysis

1 INTRODUCTION

AlGaN/GaN HEMTs are now receiving great interest for application to high-power microwave devices and high-power switching devices [1, 2]. However, the breakdown voltage is known to be greatly lower than that theoretically predicted. To improve the breakdown voltage, the introduction of field plate is shown to be effective both experimentally and theoretically [3-5]. But the introduction of field plate may increase the parasitic capacitance, leading to degrading the high-frequency performance. In a previous work, as another method to improve the breakdown voltage, we proposed a structure including a high-k passivation layer, and showed that the breakdown voltage increased significantly [6, 7]. We assumed an undoped semi-insulating buffer layer where a deep donor compensates a shallow donor. Recently, Fe- and Cr-doped semi-insulating buffer layers are often adopted and they acts as deep acceptors [8-12]. Therefore, in this work, we analyze AlGaN/GaN HEMTs with a buffer layer where a deep acceptor above the midgap is considered, and studied how the breakdown voltage is influenced by deep acceptors in the buffer layer.

2 PHYSICAL MODELS

Figure 1 shows a device structure analyzed in this study. The gate length L_G is 0.3 μm and the gate-to-drain distance

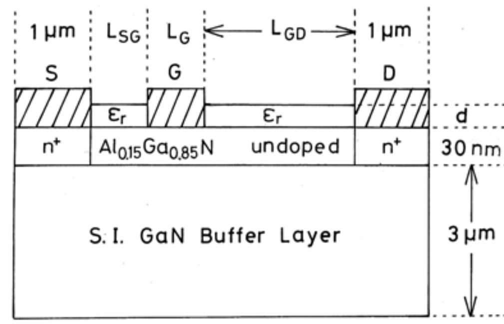

Figure 1: Device structure analyzed in this study.

L_{GD} is 1.5 μm. The thickness of passivation layer d is 0.1 μm. The relative permittivity of the passivation layer ε_r is varied between 1 and 60. Polarization charges of 10^{13} cm^{-2} are set at the heterojunction interface, and the surface polarization charges are assumed to be compensated by surface-state charges, as in [3, 5]. As a buffer layer, we consider a Fe-doped semi-insulating buffer layer. The Fe-level (E_{DA}) is set to 0.5 eV below the bottom of conduction band, and it is considered to be a deep acceptor [8, 12]. Here the deep acceptor acts as an electron trap. The deep-acceptor density N_{DA} is set to 10^{17} cm^{-3}.

Basic equations to be solved are Poisson's equation including the ionized deep-acceptor term and continuity equations for electrons and holes including a carrier generation rate by impact ionization and a carrier loss rate via the deep acceptor [7, 13-15]. These equations are expressed as follows.

1) Poisson's equation

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

2) Continuity equations for electrons and holes

$$\nabla \bullet J_n = -qG + qR_{DA} \quad (2)$$

$$\nabla \bullet J_p = qG - qR_{DA} \quad (3)$$

where N_{DA}^- is the ionized deep-acceptor density, and R_{DA} represents a carrier recombination rate via the deep acceptor. G is a carrier generation rate by impact ionization, and given by

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

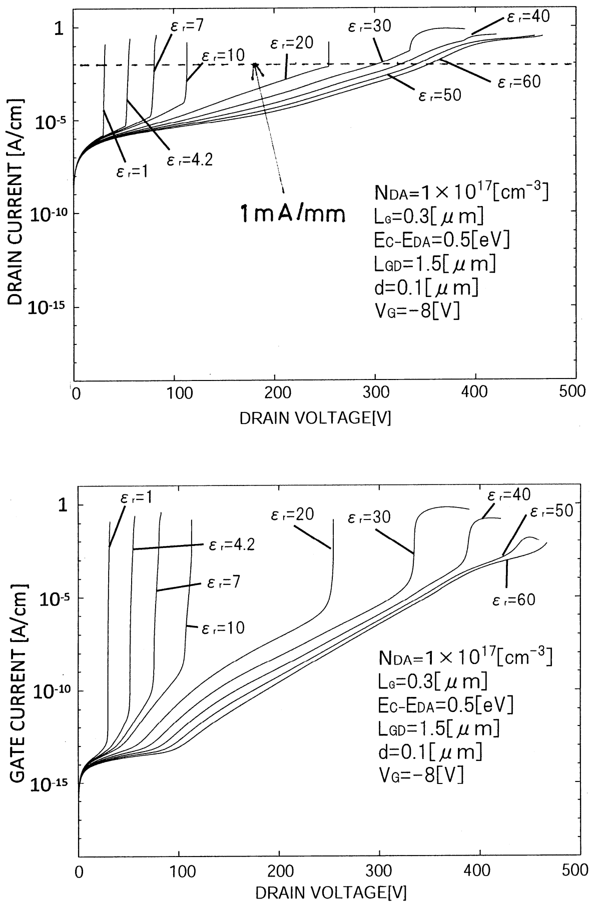

Figure 2: Calculated (a) $I_D - V_D$ curves and (b) $I_G - V_D$ curves of AlGaN/GaN HEMTs with a buffer layer including only a deep acceptor, where $E_C - E_{DA}$ = 0.5 eV and $N_{DA} = 10^{18}$ cm^{-3}. $V_G = -8$ V.

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

$$\alpha_n = A_n \exp(-B_n / |E|) \tag{5}$$

$$\alpha_p = A_p \exp(-B_p / |E|) \tag{6}$$

where E is the electric field. A_n, B_n, A_p, and B_p are deduced from [16].

The above basic equations are put into discrete forms and solved numerically.

3 CALCULATED RESULTS AND DISCUSSIONS

Figure 2 shows calculated I_D-V_D curves and I_G-V_D curves as a parameter of the relative permittivity of passivation layer ε_r. The gate voltage $V_G = -8$ V, which corresponds to an off state. When ε_r is low ($\leq$ 10), a sudden increase in drain current due to impact ionization determines the breakdown voltage V_{br}. When ε_r becomes

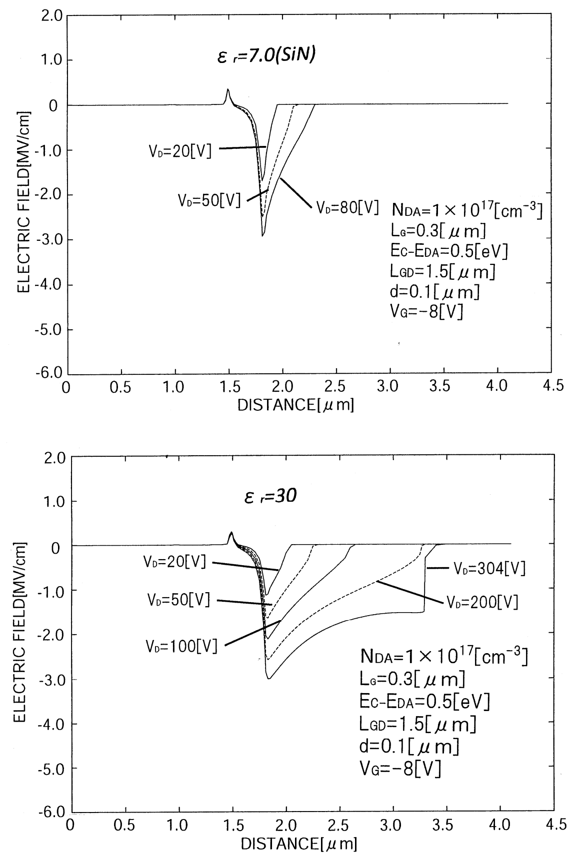

Figure 3: Comparison of electric field profiles along the heterojunction interface, corresponding to Fig.2. $V_G = -8$ V. (a) $\varepsilon_r = 7$, (b) $\varepsilon_r = 30$.

high ($\geq$ 30), I_D reach a critical value (1 mA/mm) before a sudden increase in I_D, and in this case the buffer leakage current determines V_{br}. Note that V_{br} is defined here as the drain voltage when I_D becomes 1 mA/mm. Anyway, V_{br} increases as ε_r increases.

Figure 3 shows the electric field profiles along the AlGaN/GaN heterojunction interface when ε_r is different. When ε_r is 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 = 80 V (Fig.2). However, as seen in Fig. 3(b), when ε_r becomes 30, 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 = 304 V, which is the breakdown voltage.

Figure 4 compares V_{br} versus ε_r curves between the two cases with different buffer layers. In the undoped semi-insulating buffer layer, the deep donor's energy level (E_{DD}) is set equal to E_{DA} in the Fe-doped semi-insulating buffer layer. The deep-acceptor densities N_{DA} are both set to 10^{17} cm^{-3}. V_{br} is nearly equal when ε_r is low, but becomes a little

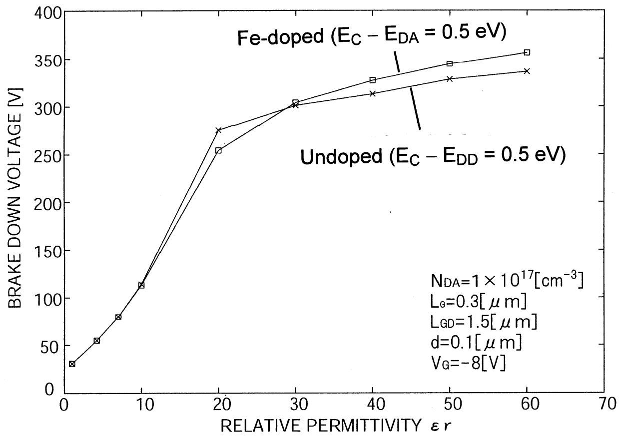

Figure 4: Comparison of breakdown voltage V_{br} versus ε_r curves between the two cases with different types of buffer layers, where E_{DA} is set equal to E_{DD}.

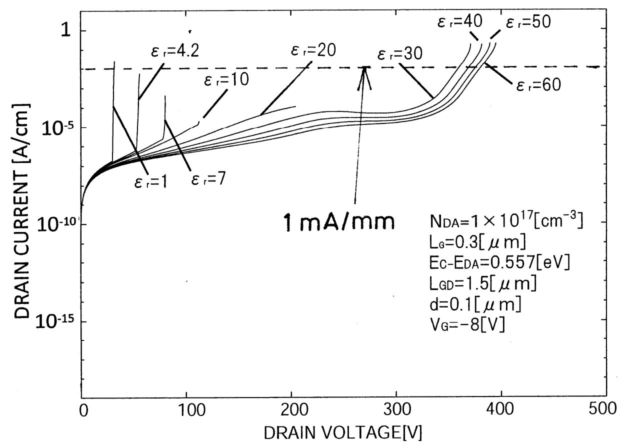

Figure 5: Calculated I_D – V_D curves of AlGaN/GaN HEMTs with a buffer layer including only a deep acceptor, where $E_C - E_{DA}$ = 0.56 eV. V_G = – 8 V.

higher in the case of Fe-doped buffer layer when ε_r is high. This is because the Fermi level in the bulk of buffer layer is a little further from the conduction band in the case of Fe-doped buffer layer, and hence the buffer leakage current becomes lower.

Figure 5 shows I_D-V_D curves when E_{DA} is 0.56 eV below E_C, a little deeper than in Fig. 2(a). The sudden increase in I_D when ε_r is low is similar to Fig. 2(a). But when ε_r is high ($\geq$ 30), the four curves become similar and the drain currents reach a critical value without showing sudden current increases. In these cases, the buffer leakage currents determine the breakdown voltages, and they are lower than those in Fig.2(a).

Figure 6 shows the comparison of V_{br} versus ε_r curves with different E_{DA}. When E_{DA} is deeper, V_{br} in high ε_r region is rather higher. This is because the buffer leakage current becomes lower, as seen in Figs.2(a) and 5. This lower buffer leakage current is due to the higher electron barrier at the channel-buffer interface.

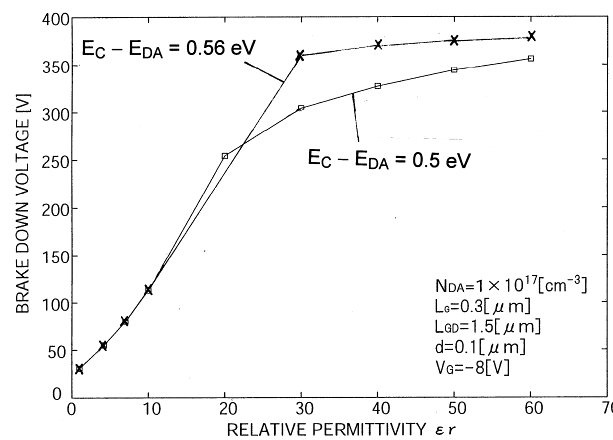

Figure 6: Comparison of breakdown voltage V_{br} versus ε_r curves between the two cases with different E_{DA}.

4 CONCLUSION

We analyze AlGaN/GaN HEMTs with a buffer layer where a deep acceptor above the midgap is considered, and studied how the off-state breakdown voltage is influenced by introducing a high-*k* passivation layer. As a result, it is shown that the breakdown voltage improves as in a case with a deep donor whose energy level is set equal to the acceptor's energy level, and also the breakdown voltage becomes a little higher in the region where the relative permittivity of the passivation layer is high. In addition, it is also shown that the breakdown voltage becomes higher in the high-k region when the deep-acceptor's energy level is deeper, because the buffer leakage current becomes smaller.

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] 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.

[4] 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.
[5] 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.
[6] 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.
[7] 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.
[8] M. Silvestri, M. J. Uren, and M. Kuball, "Iron-induced deep-acceptor center in GaN/AlGaN high electron mobility transistors: Energy level and cross section", Appl. Phys. Lett. Vol.102, pp.073051-1–073051-4, 2013.
[9] G. Verzellesi, L. Morassi, G. Meneghesso, M. Meneghini, E. Zanoni, G. Pozzovivo, S. Lavanga, T. Detzel, O. Häberlen, and G. Curatola, "Influence of carbon doping on pulsed and AC behavior of insulated-gate field-plated power AlGaN/GaN HEMTs", IEEE Electron Device Lett. vol.35, pp.443-445, 2014.
[10] S. Gusafsson, Jr-T. Chen, J. Bergten, U. Forsberg, M. Thorsell, E. Janzén, and N. Rorsman, "Dispersive effects in microwave AlGaN/AlN/GaN HEMTs with carbon-doped buffer", IEEE Trans. Electron Devices, vol.62, pp.2162-2169, 2015.
[11] J. Hu, S. Stoffels, S. Lenci, G. Groeseneken, and S. Decoutere, "On the identification of buffer trapping for bias-dependent dynamic R_{ON} of AlGaN/GaN Schottky barrio diode with AlGaN:C back barrier", *IEEE Electron Device Lett.*, vol.37, pp.310-313, 2016.
[12] Y. S. Puzyrev, R. D. Schrimpf, D. M. Fleetwood, and S. T. Pantelides, "Role of Fe impurity complexes in the degradation of GaN/AlGaN high-
[13] 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.
[14] 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.
[15] 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.
[16] C. Bulutay, "Electron initiated impact ionization in AlGaN alloys", Semicond. Sci. Technol., vol.17, pp.59-62, 2002.