Analysis of High Average Breakdown Fields between Gate and Drain in AlGaN/GaN HEMTs with High-*k* Passivation Layer

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ABSTRACT

We make a two-dimensional analysis of breakdown characteristics of AlGaN/GaN HEMTs with a high-*k* passivation layer, where a deep acceptor above the midgap is considered in a buffer layer. It is shown that the breakdown voltage V_{br} becomes higher when the relative permittivity of the passivation layer ε_r is higher. In the case where the deep-acceptor density is relatively high, V_{br} is determined by impact ionization of carriers, and it reaches about 500 V at the gate-to-drain distance L_{GD} of 1.5 μm when ε_r is 60. This corresponds to an average electric field of about 3.3 MV/cm which is nearly equal to the theoretical limit of GaN. When ε_r is higher than 30, V_{br} becomes higher when L_{GD} becomes longer, and it becomes about 930V and 1360 V when L_{GD} = 3 μm and 5 μm, respectively at ε_r = 60. These voltages correspond to average electric fields of about 3 MV/cm and 2.7 MV/cm between the gate and the drain, respectively.

Keywords: GaN HEMT, breakdown voltage, buffer latyer, deep acceptor, high-*k* passivation layer

1 INTRODUCTION

AlGaN/GaN HEMTs are now receiving great interest for application to high-power microwave devices and high power switching devices [1, 2]. To improve the power performance and the breakdown voltage of FETs, the introduction of field plate is shown to be effective [3-8], but it may increase the parasitic capacitance, leading to degrading the high-frequency performance. The average electric field at breakdown between the gate and the drain is usually about 1 MV/cm. In a previous work [9, 10], as another method to improve the breakdown voltage of AlGaN/GaN HEMTs, we proposed a structure including a high-*k* passivation layer, and showed that the breakdown voltage increased significantly. We assumed an undoped semi-insulating buffer layer where a deep donor compensates a deep acceptor. Recently, Fe- and C-doped semi-insulating buffer layers are often adopted and they acts as deep acceptors [11-15]. Therefore, in this work, we analyze AlGaN/GaN HEMTs with a buffer layer including only a deep acceptor, and studied how the breakdown voltage is influenced by its density and the gate-to-drain distance.

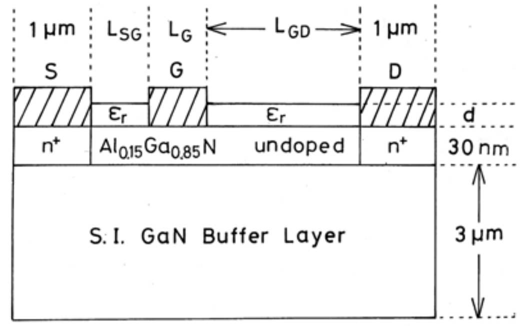


Figure 1: Device structure analyzed in this study

2 PHYSICAL MODEL

A device structure analyzed here is shown in Fig.1. The gate length is 0.3 μm and the gate-to-drain distance L_{GD} is varied between 1.5 μm and 5 μm. The passivation layer's thickness is 0.1 μm. We vary the relative permittivity of the passivation layer ε_r as a parameter. Here, we adopt a Fe-doped semi-insulating buffer layer, where the Fe-related level (E_{DA}) is set to 0.5 eV below the bottom of conduction band [11, 15]. The Fe-related level is a deep acceptor. The deep acceptors act as electron traps. The deep-acceptor density N_{DA} is set to 10^{17} cm^{-3} and $2x10^{17}$ cm^{-3} [16, 17]. Basic equations to be solved are Poisson's equation having the ionized deep-acceptor density term and electron and hole continuity equations which include a carrier loss rate via the deep acceptor and an impact ionization rate [10, 18-20] and these are solved numerically.

3 DEPENDENCE ON DEEP-ACCEPTOR DENSITY

Figs.2 and 3 shows calculated off-state drain current (I_D) – drain voltage (V_D) curves as a parameter of the relative permittivity of passivation layer ε_r, where N_{DA} is 10^{17} and $2x10^{17}$ cm^{-3}, respectively. Here, L_{GD} = 1.5 μm. In both cases, when ε_r is low (≤ 10), a sudden increase in drain current due to impact ionization determines the breakdown voltage V_{br}. In this region, the drain current becomes equal to the gate current. In the case of N_{DA} = 10^{17} cm^{-3}, when ε_r becomes high (≥ 30), I_D reach a critical value (1 mA/mm) before a sudden increase in I_D. In this case the drain current is much higher than the gate current, and hence the buffer

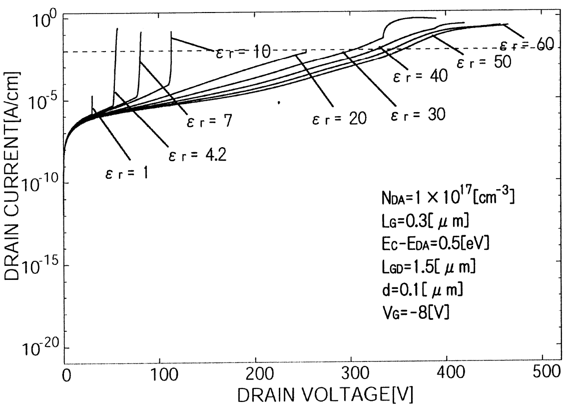


Figure 2: Calculated off-state (a) I_D – V_D curves and (b) I_G – V_D curves when N_{DA} = 10^{17} cm^{-3}. The dotted lines indicate 1 mA/mm.

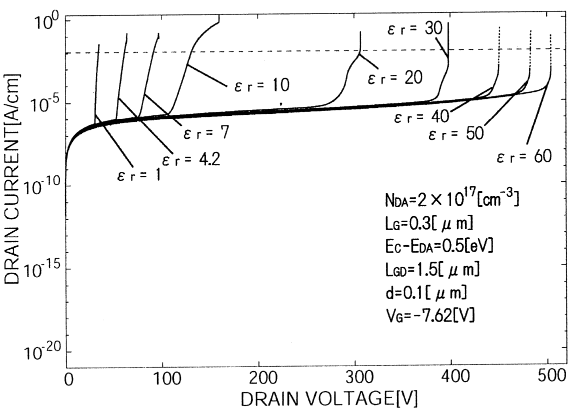


Figure 3: Calculated off-state (a) I_D – V_D curves and (b) I_G – V_D curves when N_{DA} = $2x10^{17}$ cm^{-3}. The dotted lines indicate 1 mA/mm.

leakage current determines V_{br}. Note that V_{br} is defined here as the drain voltage when I_D becomes 1 mA/mm. In Figs.2 and 3, V_{br} increases as ε_r increases. This is because the electric field at the drain edge of the gate is reduced when ε_r becomes high. In the case of N_{DA} = $2x10^{17}$ cm^{-3}, even if ε_r becomes high ($\geq$ 30), I_D increase suddenly due to impact ionization of carriers and I_D is nearly equal to I_G in this region, and the breakdown voltages are higher than those for N_{DA} =10^{17} cm^{-3}. This is because the buffer leakage current is reduced for N_{DA} = $2x10^{17}$ cm^{-3} due to a steeper barrier at the channel-buffer interface [21]. In the case of ε_r is 60, V_{br} reaches about 500 V, which corresponding to an average electric field of about 3.3 MV/cm between the gate and the drain. This value is nearly equal to the theoretical limit of GaN. Fig.4 shows electric field profiles at the heterojunction interface for the case of N_{DA} = $2x10^{17}$ cm^{-3}. Here, ε_r is 60. The electric field profiles are almost uniform at V_D = 504 V.

4 DEPENDENCE ON GATE-TO-DRAIN DISTANCE

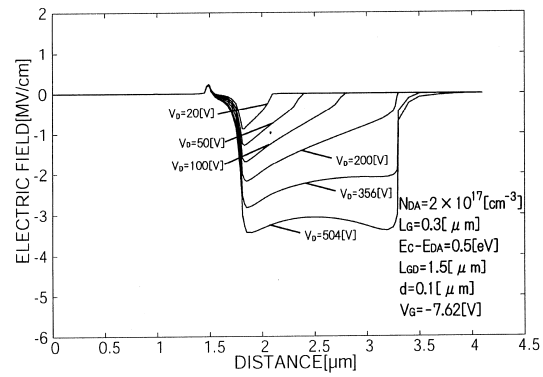


Figure 4: Electric field profiles along the heterojunction interface. ε_r = 60. N_{DA} = $2x10^{17}$ cm^{-3}. L_{GD} =1.5 μm.

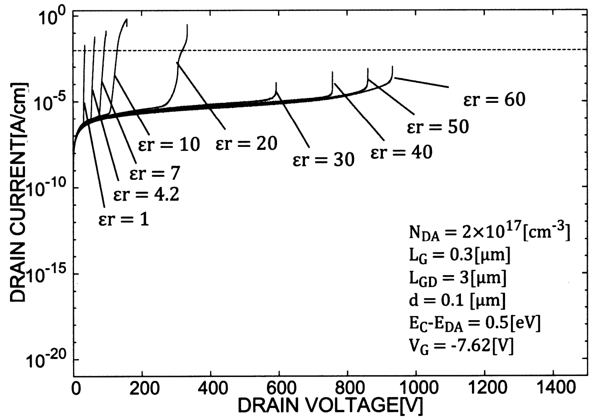


Figure 5: Calculated off-state I_D – V_D curves of AlGaN/GaN HEMTs when L_{GD} = 3 μm. N_{DA} = $2x10^{17}$ cm^{-3}.

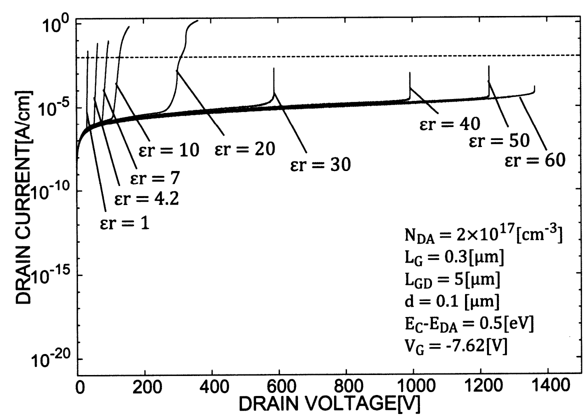


Figure 6: Calculated off-state I_D – V_D curves of AlGaN/GaN HEMTs when L_{GD} = 5 μm. N_{DA} = $2x10^{17}$ cm^{-3}.

Figs.5 and 6 show calculated off-state I_D-V_D curves as a parameter of ε_r, where the gate-to-drain distance L_{GD} is 3 μm and 5 μm, respectively. Here, N_{DA} = $2x10^{17}$ cm^{-3}. In both cases, I_D increases suddenly due to impact ionization of carriers because in the region where I_D increases suddenly, I_D is nearly equal to the gate current I_G (not shown here), as is similar to the case shown in Fig.3. When

ε_r is high, the onset voltage for current rise becomes higher in the case of longer L_{GD} (5 μm). Although in some cases, I_D does not reach 1 mA/mm due to the convergence problem, we regard this onset voltage as the breakdown voltage. Fig.7 shows the breakdown voltage V_{br} as a function of ε_r, with L_{GD} as a parameter. It is seen that when ε_r becomes higher than 30, V_{br} becomes higher when L_{GD} becomes longer. In the case of ε_r = 60, V_{br} becomes about 930 V and 1350 V, respectively when L_{GD} is 3 μm and 5μm. These voltages correspond to average electric fields of about 3.1 MV/cm and 2.7 MV/cm between the gate and the drain, respectively. These values are close to the theoretical limit of GaN (~ 3.3 MV/cm). These suggest that the electric field profiles may be rather uniform between the gate and the drain in these cases

Fig.8 shows a comparison of electric field profiles at the heterojunction interface between the two cases with (a) L_{GD} = 3 μm and (b) L_{GD} = 5 μm. Here, ε_r is 60. When L_{GD} = 3 μm, the high electric field region reaches the drain at V_D = 420 V, as seen in Fig.8(a). On the other hand, when L_{GD} = 5 μm, it reaches the drain at V_D = 800 V, as seen in Fig.8(b). At this voltage, when L_{GD} = 3 μm, the electric fields at the drain side become very high (~ 3 MV/cm), and the electric field at the drain edge of the gate becomes higher than 3 MV/cm. Then, at V_D = 932 V which is the breakdown voltage, the electric field at the drain edge of the gate reaches the critical electric field, resulting in breakdown. On the other hand, when L_{GD} = 5 μm, the electric field at the drain edge of the gate is around 3 MV/cm at V_D = 800 V. Then, the electric fields between the gate and the drain increase, leading to the breakdown at V_D = 1362 V where the electric field at the drain edge of the gate reaches the critical electric filed. Therefore, the breakdown voltage becomes higher for longer L_{GD}. It is also seen that at the breakdown, electric field profiles between the gate and the drain are rather uniform in both cases.

5 CONCLUSION

A two-dimensional analysis of breakdown characteristics of AlGaN/GaN HEMTs with a high-*k* passivation layer has been performed, where a deep acceptor above the midgap is considered in the buffer layer. It has been ascertained that the breakdown voltage V_{br} becomes higher when the relative permittivity of the passivation layer ε_r is higher. In the case where the deep-acceptor density is relatively high, V_{br} is determined by impact ionization of carriers, and it reaches about 500 V at the gate-to-drain distance L_{GD} of 1.5 μm when ε_r is 60. This corresponds to an average electric field of about 3.3 MV/cm between the gate and the drain. This value is nearly equal to the theoretical limit of GaN. It has also been shown that when ε_r is higher than 30, V_{br} becomes higher when L_{GD} becomes longer, and it becomes about 932 V and 1362 V when L_{GD} = 3 μm and 5 μm, respectively at ε_r = 60. These values correspond to average electric fields of about 3 MV/cm and 2.7 MV/cm between the gate and the drain, respectively.

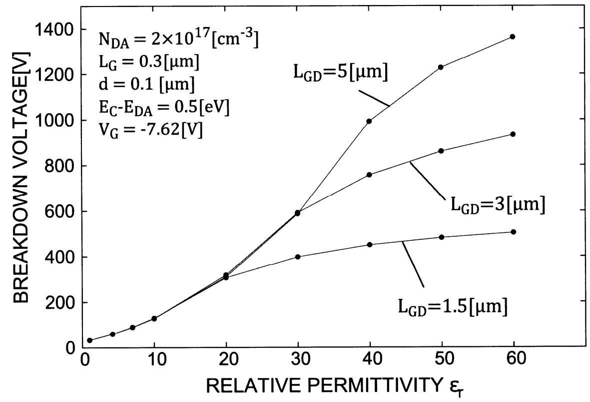
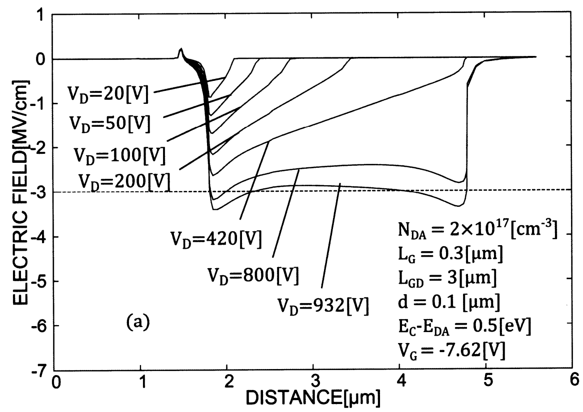


Figure 7: Breakdown voltage V_{br} versus ε_r curves as a parameter of L_{GD}. N_{DA} = 2x10^{17} cm^{-3}.



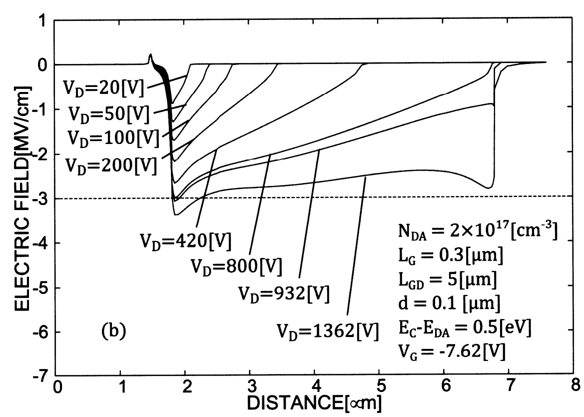


Figure 8: Electric field profiles along the heterojunction interface.. N_{DA} = 2x10^{17} cm^{-3} and ε_r = 60. (a) L_{GD} = 3 μm, (b) L_{GD} = 5 μm.

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