Simulation of Breakdown Characteristics of AlGaN/GaN HEMTs with Double Passivation Layers

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ABSTRACT

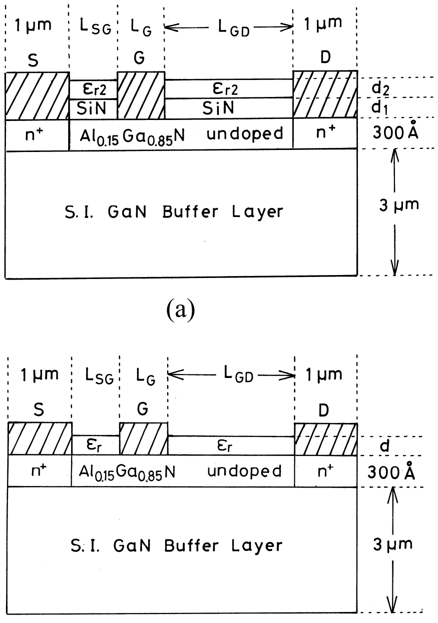
Two-dimensional analysis of off-state drain current-drain voltage characteristics in AlGaN/GaN high electron mobility transistors is performed; where two cases with a single passivation layer (SiN or high-*k* dielectric) and double passivation layers (SiN and high-*k* dielectric) are compared. It is shown that in the case of double passivation layers, the breakdown voltage is enhanced significantly as compared to the case of SiN single passivation layer when comparing at the same insulator thickness. This is because the electric field around the drain edge of gate is weakened. However, it is lowered remarkably as compared to the case with a high-*k* single passivation layer even if the first SiN layer is rather thin. Also, in the case of double passivation layers, the breakdown voltage is shown to become close to the case with high-*k* passivation layer when the relative permittivity of the second passivation layer becomes high and the SiN layer is thin.

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

1 INTRODUCTION

Because of the superior material properties of GaN, AlGaN/GaN high electron mobility transistors (HEMTs) have a great potential for high-power microwave devices and high-power switching devices [1, 2]. It is known that introducing a field plate improves the power characteristics of AlGaN/GaN HEMTs as well as GaAs-based devices [3-5]. This is because the field plate can reduce so-called current collapse [6, 7], and also increase the breakdown voltage [8-10]. The increase in breakdown voltage occurs because the electric field at the drain edge of gate is weakened by introducing the field plate. However, the field plate should increase a parasitic capacitance, resulting in degrading the high frequency characteristics.

To increase the breakdown voltage, the introduction of passivation layer with high permittivity is also considered [11-13]. In fact, introducing a high-*k* material can smooth electric field profiles between gate and drain [11]. As in Si MOSFETs, the high-*k* material is investigated as a gate insulator in AlGaN/GaN MISHEMTs [14-16]. In the AlGaN/GaN MISHEMTs, HfO_2 (relative permittivity ~ 20), La_2O_3 (~ 27), $LaLuO_3$ (~ 28) and TiO_2 (~ 55) etc. are investigated [14-16]. In our previous works [12, 13], the high-*k* dielectric was considered only as a passivation layer, and we calculated off-state breakdown characteristics in AlGaN/GaN HEMTs as a parameter of relative permittivity of thepassivation layer ε_r. As a result, it was shown that the breakdown voltage increased as ε_r increased. This was an interesting result. But, when the high-*k* materials are used, the structure should have high interface-state densities which may lead to the degradation of device performance due to the trapping effects. Therefore, in this work, we propose a structure with double passivation layers having a thin SIN layer with low interface-state densities and a relatively thick high-*k* dielectric layer. Then, we study whether the breakdown voltage is enhanced in this structure.



(a)

(b)

Figure 1: Device structures analyzed in this study. (a) Double passivation layers, (b) single passivation layer.

2 PHYSICAL MODEL

Fig.1(a) shows a device structure with double passivation layers analyzed here. For comparison, a structure with a single passivation layer (Fig.1(b)) is also analyzed. The gate length L_G is and the gate-to-drain distance L_{GD} are 0.3 μm and 1.5 μm, respectively. The thickness of first SiN layer d_1, the second layer's thickness

d_2, and its relative permittivity ε_{r2} are varied as parameters. 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}. Basic equations are Poisson's equation and continuity equations for electrons and holes [10, 20, 21], and these are solved numerically.

3 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 with (a) a single passivation layer (SiN; $\varepsilon_r = 7$) and (b) double passivation layers having a high-*k* dielectric ($\varepsilon_{r2} = 20$). Here, $d_1 = 0.01$ μm and d_2 is varied. The gate voltage is – 8 V. The threshold voltages are about – 6 V, and hence these are off-state breakdown characteristics. As seen in Fig.2(a), in the case of a single passivation layer (SiN), the drain current increases suddenly, resulting in the breakdown. This occurs due to impact ionization of carriers, so the breakdown voltage is determined by impact ionization of carriers in this case. Also, in the case with double passivation layers, the drain current increases suddenly when d_2 is relatively thin. However, as d_2 becomes thick, the drain current becomes to increase gradually and the onset voltage for current rise increases. Then, the drain current reaches a critical value (1 mA/mm) before the abrupt increase in the drain current. In this case, the buffer leakage current determines the breakdown voltage. This higher breakdown voltage is because the electric field at the drain edge of gate is reduced in the case with double passivation layers having a high-*k* dielectric, as described below.

Fig.3 shows a comparison of electric field profiles along the AlGaN/GaN heterojunction interface between the two cases with (a) single passivation layer (SiN, $d = 0.2$ μm) and (b) double passivation layers, where $d_1 = 0.01$ μm and $d_2 = 0.19$ μm. In the case of single passivation layer (SiN; $\varepsilon_r = 7$), the increase in the drain voltage is entirely applied along the drain edge of gate, leading to breakdown around $V_D = 103$ V. On the other hand, in the case of double passivation layers having a high-*k* dielectric ($\varepsilon_{r2} = 20$), the electric field around the drain edge of gate is weakened, as seen in Fig.3(b) and the peak is around 2.2 MV/cm at $V_D = 100$ V. As the drain voltage becomes higher, the high electric field region extends toward the drain, and the electric field at the gate edge of drain becomes high at $V_D = 200$ V. Finally, the peak of electric field at the drain edge of gate becomes ~ 3 MV/cm at $V_D = 288$ V. This voltage corresponds to the breakdown voltage. Therefore, the breakdown voltage becomes higher in the case of double passivation layers having a high-*k* dielectric.

Fig.4 shows the breakdown voltage V_{br} versus insulator thickness (d or $d_1 + d_2$) relationships as a parameter of d_1.

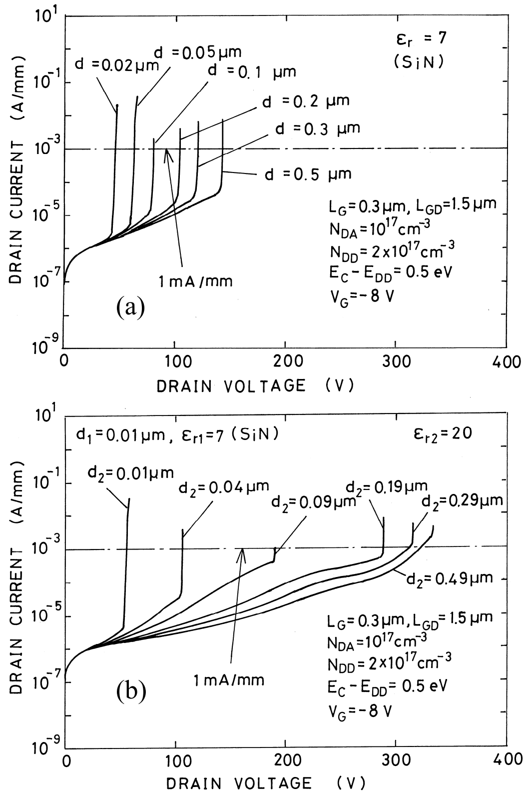


Figure 2: Calculated off-state I_D-V_D curves. (a) Single passivation layer ($\varepsilon_r = 7$), (b) double passivation layers ($\varepsilon_{r2} = 20$).

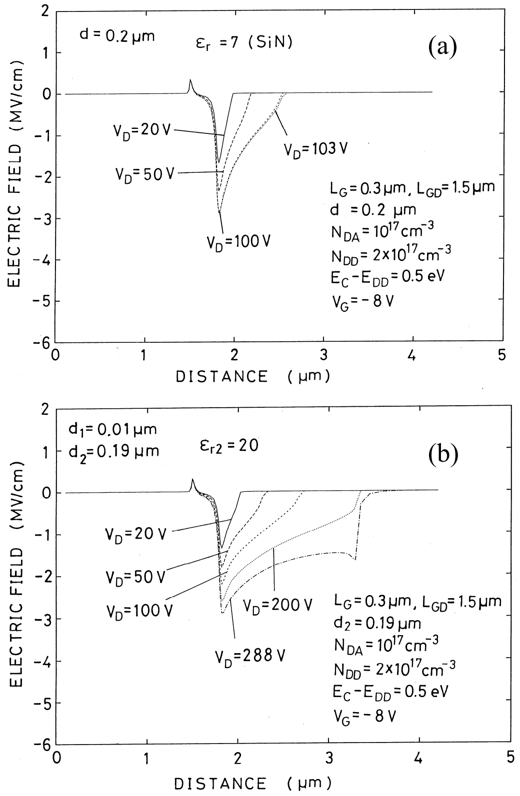


Figure 3: Electric field profiles along the heterojunction interface. (a) Single passivation layer ($\varepsilon_r = 7$), (b) double passivation layers ($\varepsilon_{r2} = 20$).

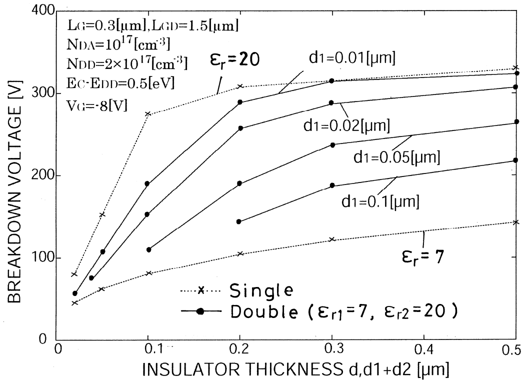


Figure 4: Breakdown voltage versus insulator thickness curves as a parameter of SiN layer thickness d_1. $\varepsilon_{r2} = 20$.

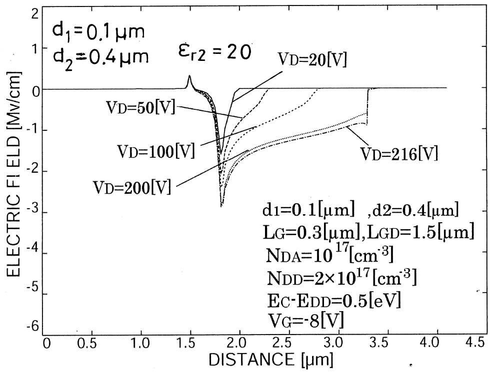


Figure 5: Electric field profiles along the heterojunction interface. $d_1 = 0.1$ μm and $d_2 = 0.4$ μm. $\varepsilon_{r2} = 20$.

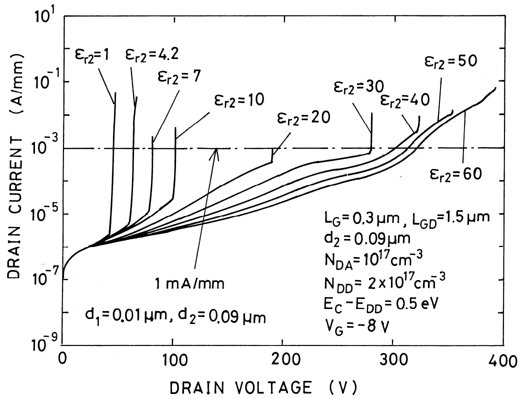


Figure 6: Calculated off-state I_D-V_D curves as a parameter of second layer's relative permittivity ε_{r2}. $d_1 = 0.01$ μm and $d_2 = 0.09$ μm.

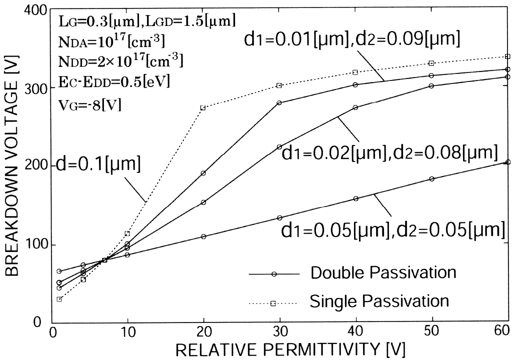


Figure 7: Breakdown voltage versus second layer's relative permittivity ε_{r2} curves as a parameter of d_1, where $d_1 + d_2 = 0.1$ μm. The dotted line shows the case of single passivation layer with $d = 0.1$ μm.

Here, the breakdown voltage is defined as a drain voltage where the drain current becomes 1 mA/mm. It is clearly seen that V_{br} is higher when d_1 is thinner. But, even if d_1 is 0.01 μm and $d_2 = 0.09$ μm, V_{br} becomes lower by about 40% than that for single passivation layer with $\varepsilon_r = 20$, although it becomes close to the value for $\varepsilon_r = 20$ as d_2 becomes thick. Then, when d_1 is thick (0.1 μm), V_{br} becomes very low even if d_2 becomes thicker. This is because, as shown in Fig.5 where $d_1 = 0.1$ μm and $d_2 = 0.4$ μm, the electric field at the drain edge of the gate is not so reduced. Therefore, to achieve the high breakdown voltage in the case with double passivation layers, it is necessary to set d_1 as thin as possible.

We next calculate a case when the relative permittivity of second passivation layer ε_{r2} is varied. Fig.6 shows calculated I_D-V_D characteristics of AlGaN/GaN HEMTs with double passivation layers as a parameter of ε_{r2}. Here, $d_1 = 0.01$ μm and $d_2 = 0.09$ μm, and so the insulator is not so thick. It is seen that although the drain current increases suddenly at relatively low voltages when ε_{r2} is low, as is similar to the case of single passivation layer (SiN), the drain current becomes to increase gradually and reach 1 mA/mm when ε_{r2} is greater than 30. In these cases, the breakdown voltage is determined by the bufferleakage current. Fig.7 shows the breakdown voltage versus ε_{r2}curve, with d_1 as a parameter. Here, $d_1 + d_2 = 0.1$ μm. For reference the case with single passivation layer ($d = 0.1$ μm) is also shown. When ε_{r2} becomes high, the breakdown voltage becomes higher. This is because the electric field at the drain edge of gate becomes lower for higher ε_{r2}. When $d_1 = 0.01$ μm and 0.02 μm, the breakdown voltage become close to the case with single passivation layer with high permittivity. But, when $d_1 = 0.05$ μm and $d_2 = 0.05$ μm, the breakdown voltage remains relatively low even if ε_{r2} becomes 60. Therefore, to achieve a high breakdown voltage, the first SiN thickness should be made as thin as possible.

4 CONCLUSION

In summary, 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 or high-*k* dielectric) and double passivation layers (SiN and relatively thick high-*k* dielectric) are considered. It has been shown that in the case of double passivation layers, the breakdown voltage is enhanced significantly as compared to the case of SiN single passivation layer when comparing at the same insulator thickness. This is because the electric field around the drain edge of gate is weakened. However in the case with relatively thin second layer, the breakdown voltage is lowered remarkably as compared to the case with a high-*k* single passivation layer even if the first SiN layer is rather thin. Also, in the case of double passivation layers, the breakdown voltage has been shown to become close to the case with high-*k* single passivation layer when the relative permittivity of the second passivation layer becomes high and the SiN layer is relatively thin.

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