Simulation of Buffer Current Effects on Breakdown Voltage in AlGaN/GaN HEMTs Having Passivation Layers with Different Permittivity

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ABSTRACT

A two-dimensional simulation of off-state breakdown characteristics in AlGaN/GaN HEMTs is performed, with the relative permittivity of passivation layer ε_r as a parameter. The simulation is made with and without impact ionization of carriers to study how the buffer leakage current affects the breakdown chracteristics. It is shown that when ε_r is low, the breakdown voltage is determined by the impact ionization of carriers, and when ε_r becomes high, it is determined by the buffer leakage current. This buffer leakage current decreases as ε_r increases because the electric field at the drain edge of the gate is weakened, and hence the breakdown voltage increases as ε_r increases.

Keywords: GaN HEMT, breakdown voltage, passivation layer, buffer leakage current, two-dimensional analysis

1 INTRODUCTION

AlGaN/GaN HEMTs are now receiving great attention because of their applications to high-frequency power devices and high-power switching devices [1, 2]. It is known that the introduction of a gate field plate improves the power performance of AlGaN/GaN HEMTs [3-5]. This is because it 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 [8, 10]. However, the field plate increases a gate parasitic capacitance. Therefore it may lead to the degradation of the high frequency performance

As another way to improve the breakdown voltage, introducing a passivation layer with high permittivity can also be considered [11, 12]. In fact, the introduction of a high-*k* layer can smooth electric field profiles between the gate and the drain [13]. 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 ($\varepsilon_r \sim 27$) and $LaLuO_3$ ($\varepsilon_r \sim 28$) etc. are studied in AlGaN/GaN MISHEMTs [14, 15]. In previous works [11, 12], 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 the passivation layer's relative permittivity ε_r, and showed that the breakdown voltage increased with ε_r. But we calculated only the case with impact ionization, and it was not clear how the buffer leakage current affected the breakdown voltage. Therefore, in this work, we simulate the off-state drain current - drain voltage characteristics of AlGaN/GaN HEMTs as a parameter of ε_r with and without impact ionization, and particularly study how the buffer leakage current affects the off-state breakdown voltage.

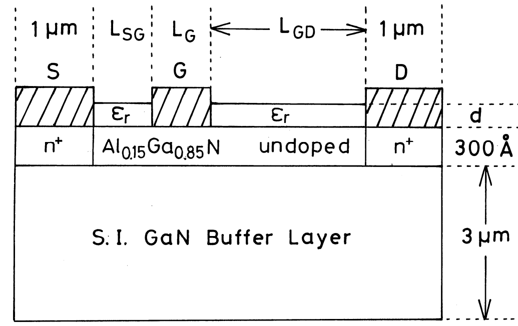

Figure 1: Device structure analyzed in this study.

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 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 4.2 and 60. Here, we don't include gate tunneling [8, 10]. We consider the breakdown due to an increase in the buffer leakage current or due to the impact ionization of carriers. In a semi-insulating buffer layer, we consider a shallow donor, a deep donor, and a deep acceptor [16-18]. 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 E_C – 0.5 eV as an energy level of the deep donor. The deep-acceptor density N_{DA} is set rather high of 10^{17} cm^{-3}. A study [19] 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, 20-22]. These equations are expressed as follows.

1) Poisson's equation

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

2) Continuity equations for electrons and holes

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

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

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

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

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

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

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

where E is the electric field. A_n, B_n, A_p, and B_p are deduced from [23].

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 of AlGaN/GaN HEMTs as a parameter of the relative permittivity of the passivation layer ε_r. Here, the gate voltage V_G is – 8 V and it is an off state. The solid lines correspond to the cases with impact ionization, and the dashed lines correspond to the cases without impact ionization. The drain currents calculated without impact ionization are normal buffer leakage currents [24, 25], which are determined by buffer trapping. They are clearly seen to be lower for higher ε_r. This is because the electric field at the drain edge of the gate is reduced in the case of higher ε_r. When ε_r is low (< 20), an abrupt increase in I_D due to impact ionization of carriers determines the off-state breakdown voltage V_{br}. On the other hand, when ε_r is high (≥ 30), the buffer leakage current reaches a critical value (1mA/mm) before the abrupt increase in I_D, and it determines V_{br}. Here, the off-state breakdown voltage V_{br} is defined as a drain voltage when I_D becomes 1 mA/mm, and the breakdown voltage becomes higher when ε_r is higher.

Figure 3 shows the electric field profiles along the AlGaN/GaN heterojunction interface when ε_r are different. When ε_r is 4.2, 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 = 55 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 = 50 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 = 301 V, which is the breakdown voltage. Note that in this case, real gate breakdown occurs around V_D = 360 V, as seen in Fig.2. Therefore, the buffer leakage current reaches the critical value before the electric field at the drain edge

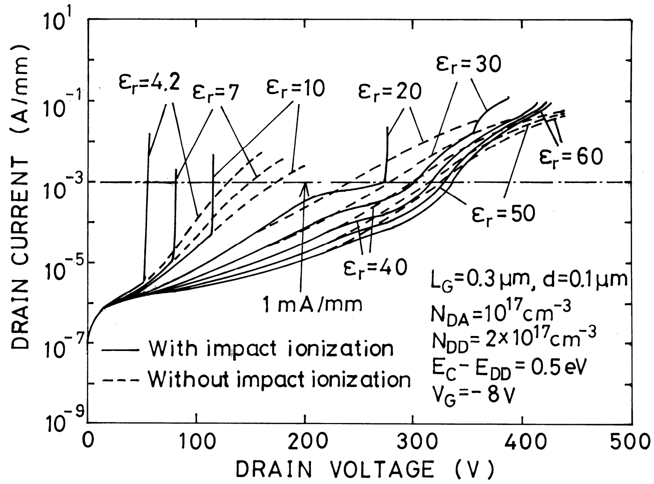

Figure 2: Calculated I_D – V_D curves of AlGaN/GaN HEMTs as a parameter of ε_r. V_G = – 8 V. L_{GD} = 1.5 μm and d = 0.1 μm.

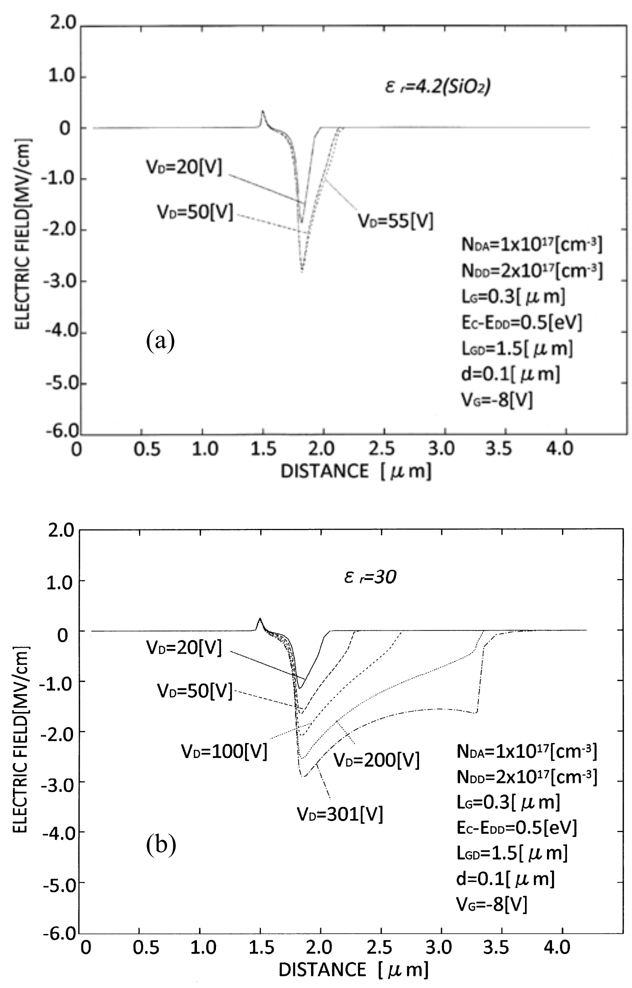

Figure 3: Electric field profiles along the heterojunction interface, with V_D as a parameter. V_G = – 8 V. (a) ε_r = 4.2, (b) ε_r = 30. d = 0.1 μm.

of the gate reaches the theoretical breakdown field of GaN (≥ 3 MV/cm).

Here, it should be mentioned that the I_D-V_D curves show complex features when ε_r is relatively high, that is, I_D with impact ionization takes both a lower and a higher value than that without impact ionization. This is originated from the fact that holes are generated by impact ionization between the gate and the drain and they flow into the buffer layer. These holes are captured by traps, modulating potential profiles around the channel-buffer interface and affecting electron injection into the buffer layer. Electron densities as well as hole densities are increasing in the buffer layer [12, 13]. Therefore, the traps become acting as recombination centers, and hence the barrier for electrons toward the buffer raises at the drain side of the gate region to make the drain current lower than that without impact ionization [20]. On the other hand, the barrier for electrons at the source side decreases by hole trapping, resulting in the increase in the drain current and making the drain current higher than that without impact ionization particularly at high V_D. Similar features mentioned above were discussed in detail before in the case of GaAs MESFETs on a semi-insulating substrate [20].

Figure 4 shows calculated I_D-V_D curves of AlGaN/GaN HEMTs when V_G is – 10 V, with the relative permittivity of the passivation layer ε_r as a parameter. In this case V_G is more negative than in Fig.2. The solid lines correspond to the cases with impact ionization, and the dashed lines correspond to the cases without impact ionization. The drain currents calculated without impact ionization are lower than those in Fig.2, which indicates that the buffer leakage currents become lower for the case of V_G = – 10 V. This is because the depletion layer extends more into the buffer layer. Figure 5 shows V_{br} versus ε_r for the two cases with V_G = – 8 V and – 10 V. When V_G = – 10 V, V_{br} becomes lower when ε_r is low (< 20). This is because the electric field at the drain edge of the gate is higher when V_G is more negative and the breakdown due to the impact ionization of carriers occurs at lower V_D. On the other hand, V_{br} becomes higher in the region where ε_r is high (≥ 30). This is because when the gate voltage is more negative, the depletion region extends more into the buffer layer, and hence the buffer leakage current becomes smaller. Thus, the breakdown voltage determined by the buffer leakage current becomes higher.

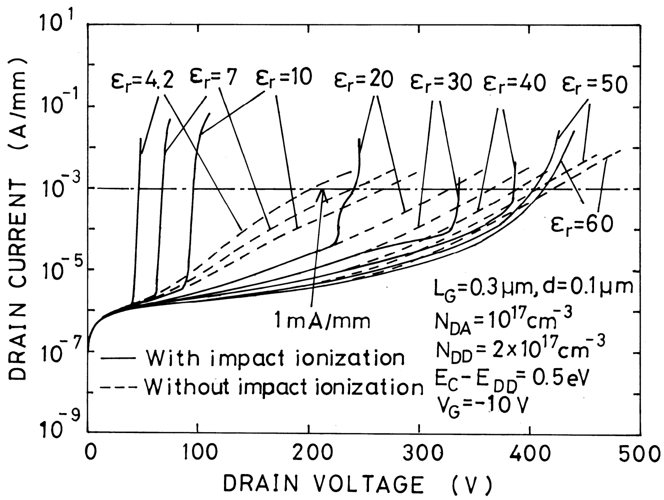

Figure 4: Calculated I_D – V_D curves of AlGaN/GaN HEMTs as a parameter of ε_r. V_G = – 10 V. L_{GD} = 1.5 μm and d = 0.1 μm.

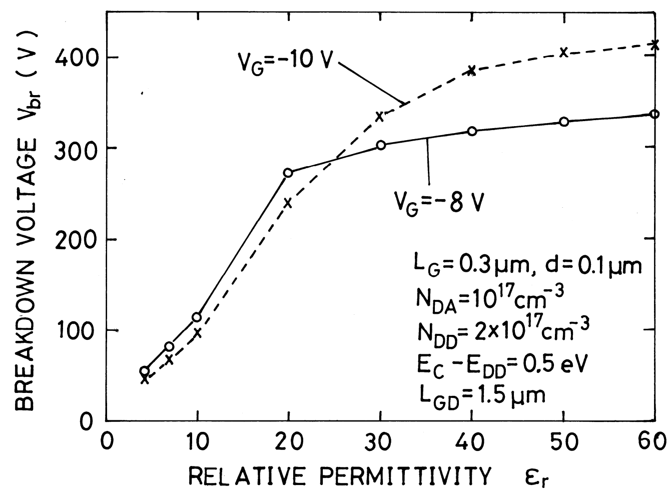

Figure 5: Calculated off-state breakdown voltage V_{br} versus ε_r for different V_G. L_{GD} = 1.5 μm and d = 0.1 μm.

4 CONCLUSION

A two-dimensional simulation of off-state breakdown characteristics in AlGaN/GaN HEMTs has been performed with and without impact ionization by considering a deep donor and a deep acceptor in the semi-insulating buffer layer. It has been shown that the buffer leakage current decreases as the relative permittivity of passivation layer ε_r increases, because the electric field at the drain edge of the gate is reduced. When ε_r is low, the impact ionization of carriers determines the off-state breakdown voltage. On the other hand, when ε_r is high, the buffer leakage current reaches a critical value and determines the breakdown voltage before the impact ionization becomes a problem. And the breakdown voltage becomes higher for higher ε_r. It has also been shown that when the gate voltage becomes more negative, the breakdown voltage in the high ε_r region increases because the buffer leakage current becomes smaller.

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