Analysis of Breakdown Characteristics in Field-Plate AlGaN/GaN HEMTs: Dependence on Deep-Acceptor Density in Buffer Layer

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ABSTRACT

We make a two-dimensional analysis of field-plate AlGaN/GaN HEMTs with a Fe-doped semi-insulating buffer layer, and studied how the deep-acceptor density in the buffer layer N_{DA} and the field-plate length L_{FP} affect the breakdown voltage V_{br} of AlGaN/GaN HEMTs. N_{DA} is varied between 10^{17} cm^{-3} and $3x10^{17}$ cm^{-3}, and the deep-acceptor's energy level is set 0.5 eV below the bottom of conduction band. L_{FP} is varied between 0 and 1 μm. The calculated off-state breakdown characteristics show that the drain current usually increases steeply due to impact ionization of carriers, resulting in breakdown. But, in some cases, V_{br} is determined by buffer leakage current. This current is larger for lower N_{DA}, and hence V_{br} becomes higher for higher N_{DA}. It is also shown that V_{br} takes a maximum value at L_{FP} = 0.2-0.3 μm when the gate-to-drain distance is 1.5 μm, and that the average electric field for breakdown between gate and drain becomes 3.2 MV/cm when N_{DA} is $3x10^{17}$ cm^{-3}.

Keywords: GaN HEMT, field plate, breakdown voltage, buffer latyer, deep acceptor

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]. This is because the field plate reduce the current collapse of the FETs, and the electric field at the drain edge of the gate is reduced.

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 first assumed an undoped semi-insulating buffer layer where a deep donor compensates a deep acceptor [9, 10]. Recently, Fe- and C-doped semi-insulating buffer layers are often adopted and they acts as deep acceptors [11-15]. Hence, we analyzed AlGaN/GaN HEMTs with a buffer layer including only a deep acceptor, and found that the breakdown voltage became higher when the acceptor density became higher [16].

Therefore, in this work, we make a two-dimensional analysis of brealdown characteristics in field-plate AlGaN/GaN HEMTs with a Fe-doped semi-insulating buffer layer, and study how the brealdown voltage is influenced by the deep acceptor density in the buffer layer.

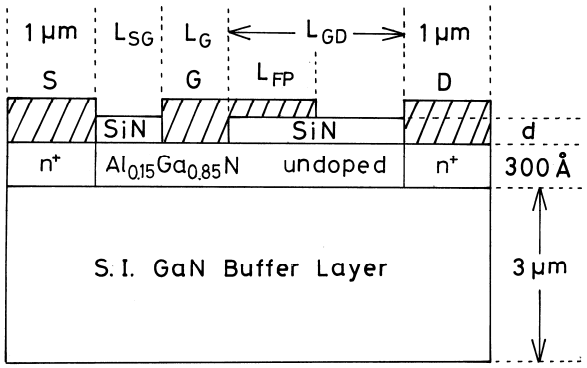


Figure 1: Device structure analyzed in this study.

2 PHYSICAL MODEL

A device structure analyzed here is shown in Fig.1. The gate length and the gate-to- drain distance is 0.3 μm and 1.5 μm, respectively. The SiN passivation layer's thickness is 0.1μm. The field-plate length L_{FP} is varied between 0 and 1 μm. 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 varied between 10^{17} and $3x10^{17}$ cm^{-3}.

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, 16-19] and expressed as follows.

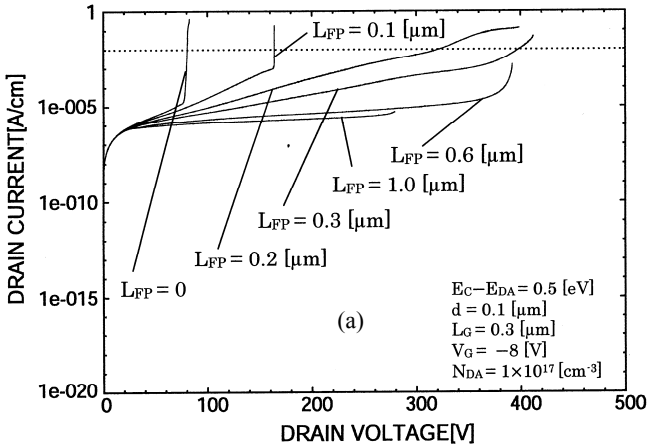
1) Poisson's equation

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

2) Continuity equations for electrons and holes

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

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



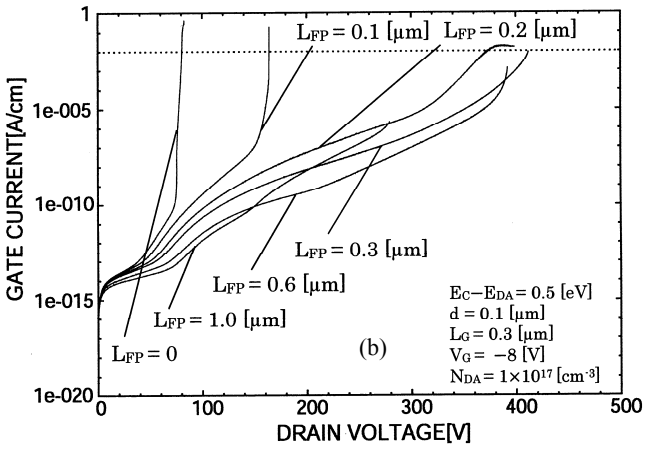
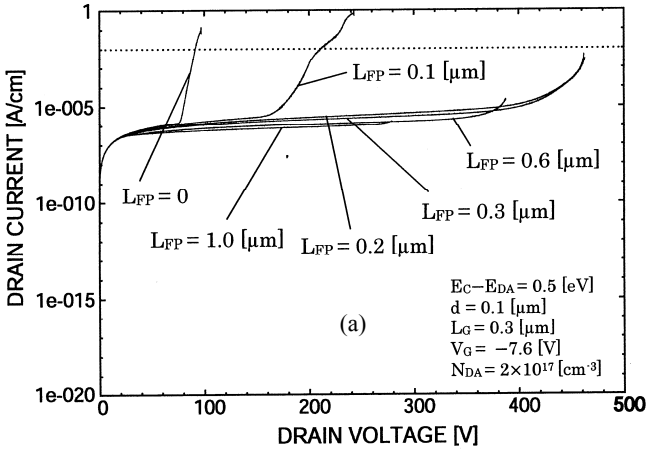


Figure 2: Calculated I_D-V_D curves and (b) I_G-V_D curves of AlGaN/GaN HEMT with $N_{DA} = 10^{17}$ cm^{-3}.



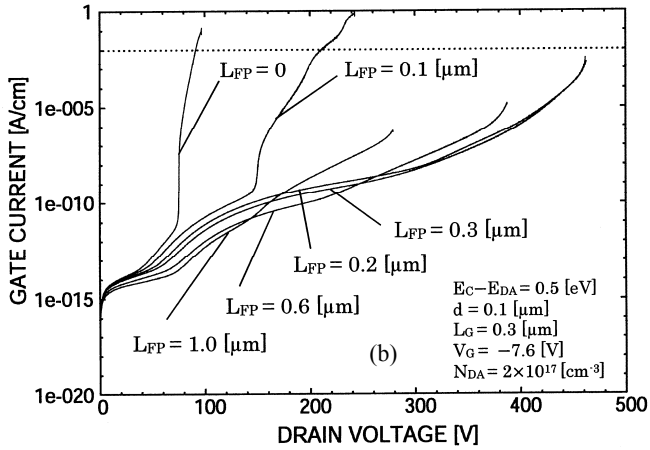


Figure 3: Calculated I_D-V_D curves and (b) I_G-V_D curves of AlGaN/GaN HEMT with $N_{DA} = 2x10^{17}$ cm^{-3}.

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

$$G = (\alpha_n \mid J_n \mid + \alpha_p \mid J_p \mid)/q \tag{4}$$

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

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

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

where E is the electric field. A_n, B_n, A_p, and B_p are deduced from [20].

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

3 RESULTS AND DISCUSSIONS

Figs.2 and 3 show calculated (a) drain current I_D – drain voltage V_D curves and (b) gate current I_G – V_D curves of field-plate AlGaN/GaN HEMTs with the field-plate length L_{FP} as a parameter. Fig.2 show the case of $N_{DA} = 10^{17}$ cm^{-3} and Fig.3 shows the case of $N_{DA} = 2x10^{17}$ cm^{-3}. In Fig.2, the gate voltage V_G is – 8 V and in Fig.3, V_G is – 7.62 V. These voltages are V_{th} – 2 V where V_{th} is the threshold voltage, so Figs.2 and 3 are off-state breakdown characteristics. At L_{FP} = 0 and 0.1 μm, I_D increases suddenly, resulting in breakdown. This is due to an abrupt increase in I_G, and I_D = I_G in this region. But, in Fig.2 ($N_{DA} = 10^{17}$ cm^{-3}), when L_{FP} = 0.2 μm and 0.3 μm, I_D increases gradually and reaches a critical current level (10^{-2} A/cm or 1 mA/mm), and in this case I_G is rather lower than I_D. Therefore, in this case the buffer leakage current determines the breakdown voltage. In other cases, the overall increase in I_D correlates well with the increase in I_G, and the breakdown voltage is determined by impact ionization of carriers. Here, we define the brealdown voltage as a drain voltage when I_D becomes 1 mA/mm (10^{-2} A/cm). So, in the cases of L_{FP} = 0.2 and 0.3 μm, the breakdown voltages are higher when $N_{DA} = 2x10^{17}$ cm^{-3}. When L_{FP} = 0.6 μm and 1 μm, I_D does not reach 1 mA/mm, but the onset voltages of current rise seems to be similar.

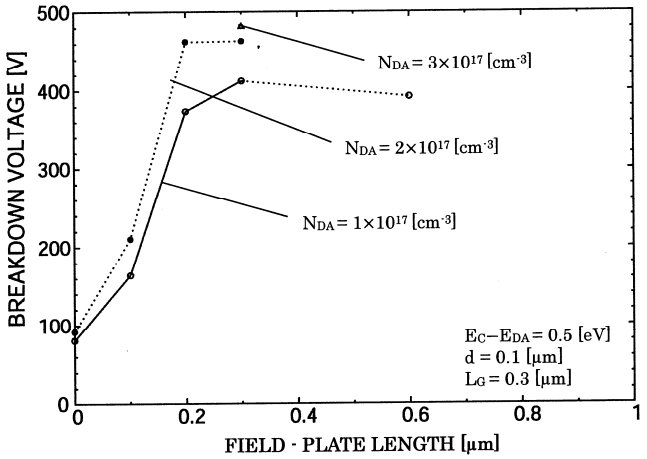


Figure 4: Breakdown voltage as a function of field-plate length L_{FP}, with N_{DA} as a parameter.

Fig.4 shows the breakdown voltage V_{br} versus L_{FP} curves as a parameter of N_{DA}. The breakdown voltage is defined here as a drain voltage when I_D becomes 1 mA/mm. It is clearly seen that V_{br} becomes higher when N_{DA} is higher, although several points are missing because I_D does not reach 1 mA/mm particularly for high N_{DA}. The higher V_{br} for higher N_{DA} should be due to the lower buffer leakage current due to a stteper barrier at the channel-buffer interface [21]. The obtained highest V_{br} here is about 480 V at N_{DA} = 3x10^{17} cm^{-3} and L_{FP} = 0.3 μm, which correspond to an average electric field of about 3.2 MV/cm between the gate and the drain. From Fig.4, we also see that there is an optimum L_{FP} to obtain a high V_{br}. Fig.5 shows a comparison of electric field profiles between the two cases with (a) L_{FP} = 0.3 μm and (b) L_{FP} = 1 μm. Here N_{DA} = 2x10^{17} cm^{-3}. In both cases, the electric field at the drain edge of the gate is reduced, and the voltage is applied between the field-plate edge and the drain. In the case of L_{FP} = 1 μm, the distance between the field-plate edge and the drain is 0.5 μm, and hence the electric field becomes very high in this region. Therefore, the breakdown voltage at L_{FP} = 1 μm becomes lower than that for L_{FP} = 0.3 μm, and the optimum value of L_{FP} appears.

4 CONCLUSION

A two-dimensional analysis of field-plate AlGaN/GaN HEMTs with a Fe-doped semi-insulating buffer layer has been performed, and it has been studied how the deep-acceptor density in the buffer layer N_{DA} and the field-plate length L_{FP} affect the breakdown voltage V_{br} of AlGaN/GaN HEMTs. The calculated off-state breakdown characteristics have shown that the drain current usually increases steeply due to impact ionization of carriers, resulting in breakdown. But, in some cases, V_{br} is determined by the buffer leakage current. This current is smaller for higher N_{DA} due to a

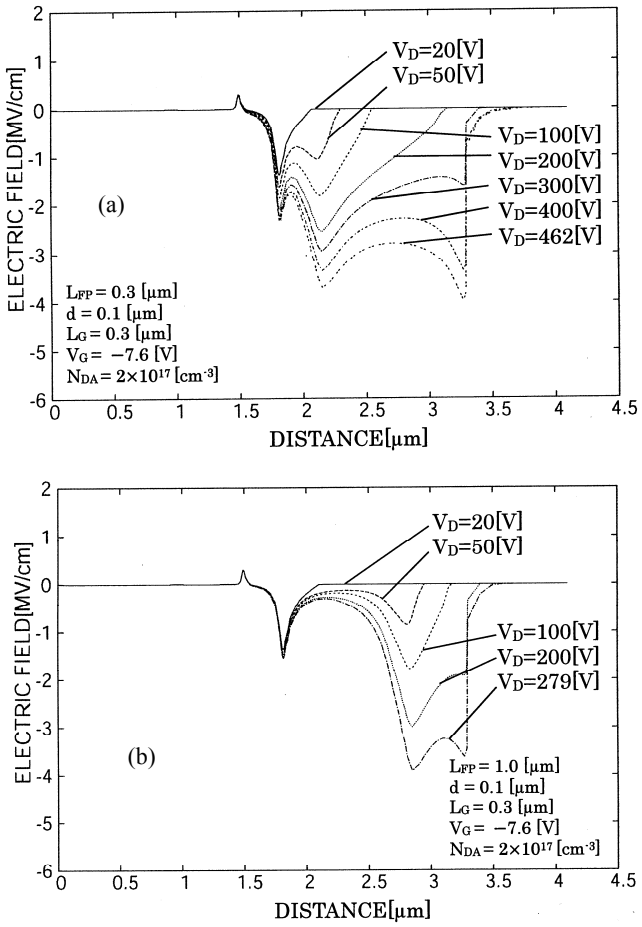


Figure 5: Comparison of electric field profiles between the two cases with (a) L_{FP} = 0.3 μm and (b) L_{FP} = 1 μm. N_{DA} = 2x10^{17} cm^{-3}.

steeper barrier at the channel-buffer interface, and hence V_{br} becomes higher for higher N_{DA}. It is also shown that V_{br} takes a maximum value at L_{FP} = 0.2-0.3 μm when the gate-to-drain distance is 1.5 μm, and that the average electric field for breakdown between the gate and the drain becomes 3.2 MV/cm when N_{DA} is 3x10^{17} cm^{-3}.

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