Simulation of Recessed-Gate AlGaN-GaN DH-HEMT for Power Electronics Applications

YASHVIR SINGH
Department of Electronics & Comm. Engg.
G. B. Pant Engineering College
Pauri Garhwal, Uttarakhand, INDIA
om_ysingh@yahoo.co.in

MOHIT PAYAL
School of Science & Engg., USIC
H. N. B. Garhwal University
Srinagar, Pauri Garhwal, Uttarakhand, INDIA
mohitpayaal1986@gmail.com

Abstract

The effects of gate-recessing on the performance parameters in AlGaN/GaN/AlGaN double-heterojunction high electron mobility transistor are presented. The accuracy of simulations is verified by comparing the simulated characteristics with the reported measured data. The results show that a 12nm gate-recessed AlGaN/GaN/AlGaN DH-HEMT provides a 61% reduction in threshold voltage, 20% increase in transconductance, 43% improvement in cut-off frequency and seven times improvement in breakdown voltage at the cost of 44% reduction in drain current compared to the device without gate-recess.

Keywords: High electron mobility transistor (HEMT), double-heterojunction, AlGaN/GaN, recessed-gate.

1 Introduction

High electron mobility transistors (HEMTs) are widely used in high frequency applications such as military communication and navigation systems. In the past few years, AlGaN/GaN based HEMTs have become an attractive semiconductor device for next generation of high-power electronics applications because Gallium Nitride (GaN) has wide band-gap, high electron saturation velocity, high critical breakdown field. The AlGaN/GaN HEMT technology offers tremendous new capabilities and is expected to transform the future of power amplifiers. For such applications, the important performance parameters of HEMT are output drain current, threshold voltage, transconductance, breakdown voltage and cut-off frequency. The characteristics of a normal single heterojunction HEMT can be improved using a double-heterojunction (DH) HEMT, employing a gate field-plate, and recessing the gate[1, 2]. The conduction losses due to on-state resistance and the off-state breakdown voltage (V_{BR}) are the main limitations of the power-switch performance. The breakdown of a GaN-based HEMTs is determined by the sub-threshold drain current exceeding the commonly used value of 0.5 mA/mm. The sub-threshold drain current is mostly dominated by two leakage currents i.e. the bulk punch-through [3] and the Schottky gate reverse bias tunnelling leakage current [4]. Suppression of these sub-threshold leakage currents would enable the enhancement of the device V_{BR}. The DH-HEMTs structures have shown the ability to suppress the current leakages and enhance the device V_{BR}, and scale it up with the device dimensions [5, 6]. The Schottky gate reverse bias leakage current depends upon the distribution of the electric field under the drain side of the gate [6]. Although, in HEMTs, the V_{BR} is improved by using field-plate methods [7, 8, 9, 10] but increase in the device capacitance limits its high frequency and switching performance. Further, it is predicted that combining field-plates and vertical potential back barrier would increase the V_{BR} of the device [1]. On the other hand, the recessed-gate technology is very attractive not only for improving the off-state V_{BR} but also for controlling the threshold voltage in the AlGaN/GaN/AlGaN DH-HEMTs.

Therefore, the motive of this work is to investigate the effect of gate-recessing in a AlGaN/GaN/AlGaN DH-HEMT employing the field plate. The device performance is evaluated using 2D numerical simulations in the device simulator, ATLAS [11]. The accuracy of simulation results is verified by implementing a reported AlGaN/GaN/AlGaN DH-HEMT structure [1] in the simulator. It is observed that there is a good agreement between the simulated results and experimental data. After this, we have studied the effects of gate-recessing on the performance parameters in the AlGaN/GaN/AlGaN DH-HEMT structure. The various performance parameters of without and with 12nm gate-recess structures are compared. It is demonstrated that a significant improvement in threshold voltage (V_{th}), transconductance (g_m)), V_{BR} and frequency (f_T) can be achieved by employing the gate-recess along with field-plate at the cost of reduction in the drain current (I_{ds}) of the device.

2 DH-HEMT Structure Simulation

Fig.1 shows the schematic cross-sectional view of the AlGaN/GaN/AlGaN DH-HEMT as reported in [1] without gate-recess and field-plate. For the AlGaN DH-buffer structure, a t_{bb}=1.7μm thick UID $Al_yGa_{1-y}N$ layer with Al mole fraction (y) of 0.10 is used. The structure has a t_c=35nm UID GaN channel layer and t_b=25nm $Al_{0.25}Ga_{0.75}N$ barrier layer. The doping concentration of the AlGaN barrier layer is $4x10^{-18}$ cm^{-3}. Ir/Ti/Au contact is used for the gate Schottky metal. The device is having a gate length (L_g) of 0.7 μm. The gate-drain offset length (L_{gd}) and gate-source offset length (L_{gs}) are taken as 10μm and 1μm, respectively. In order to check the accuracy of the simulation results, the structure is implemented in the two-dimensional device simulator and simulations are performed by invoking suitable models for Shockley-Read-Hall and Auger generation and recombination, concentration-dependent mobility, electric-field-dependent mobilities, carrier velocity saturation and impact ionization.

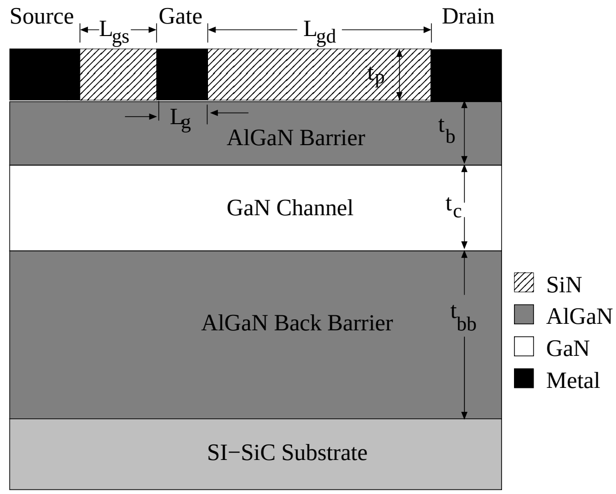

Figure 1: Cross-section of an AlGaN/GaN/AlGaN DH-HEMT

The simulated transfer characteristic of the AlGaN/GaN/AlGaN DH-HEMT along with the experimental data [1] is shown in Fig.2. It can be seen that there is a good agreement between the simulated result and measured data. This clearly confirms the accuracy of simulation results for the DH-HEMT structure. Now, we can carry out the simulations on the AlGaN/GaN/AlGaN DH-HEMT structure by modifying the structural and fabrication parameters while keeping simulation models and material dependant parameters same. Therefore, in the following section, the simulations on the AlGaN/GaN/AlGaN DH-HEMT with field-plate and gate-recess are performed to improve the device performance.

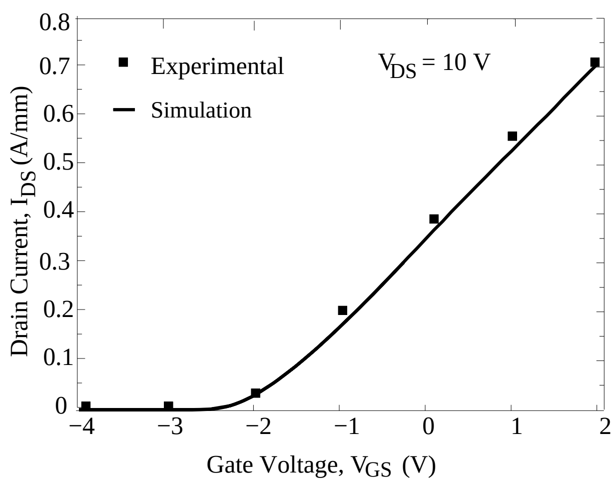

Figure 2: Simulated transfer characteristic of the AlGaN/GaN/AlGaN DH-HEMT compared with the reported experimental data [1].

3 Recessed-Gate DH-HEMT Simulation

Fig. 3 shows the cross-section of an AlGaN/GaN /AlGaN DH-HEMT with gate-recess and field-plate. This structure is same as that of Fig.1 with only difference that the field-plate of 1.3μm with 0.6μm extension toward the drain, and the gate-recessing is used. The gate-recess depth (t_d) and doping (N_D) of the AlGaN barrier layer in this structure are varied in order to see their impact on device performance parameters such as I_{ds}, V_{th}, g_m, V_{BR} and f_T as discussed in the next section. It may be noted that the material dependent parameters are kept same as that of the device shown in Fig.1.

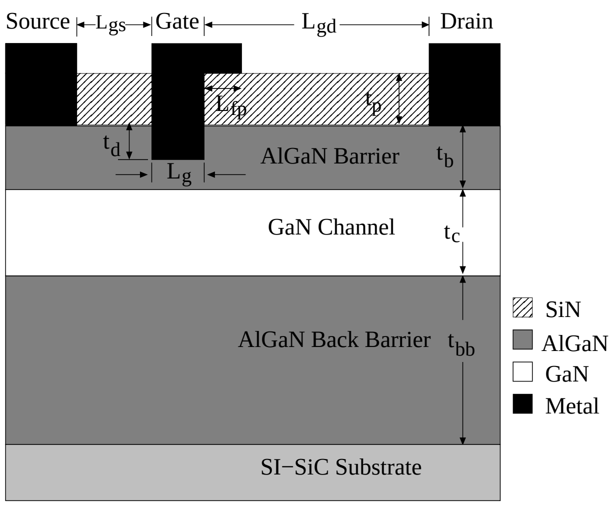

Figure 3: Cross-section of an AlGaN/GaN/AlGaN DH-HEMT with field-plate and gate-recessing.

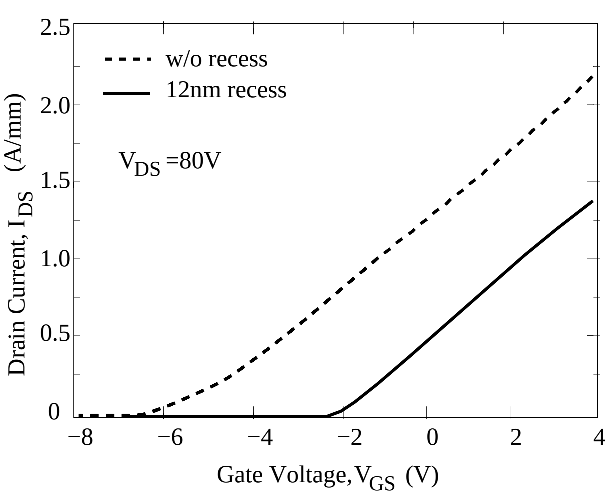

Figure 4: Transfer characteristics of the AlGaN/GaN/AlGaN DH-HEMT without and with 12nm gate-recess.

4 Results And Discussion

Fig. 4 gives the transfer characteristics of the AlGaN/GaN/AlGaN DH-HEMT without and with 12nm gate-recessing at a AlGaN barrier layer doping (N_D) of 8x10^{-18} cm^{-3}. It can seen that without gate-recess, the V_{th} of the device is -6.8V whereas it shifts to -2.6V for a gate recessing of 12nm. In other words, a 12nm gate-recess in AlGaN/GaN/AlGaN DH-HEMT provides an improvement of 61% in the V_{th}. It may be noted that the gate-recess adversely affects the drain current i.e. drain current reduces with gate-recess.

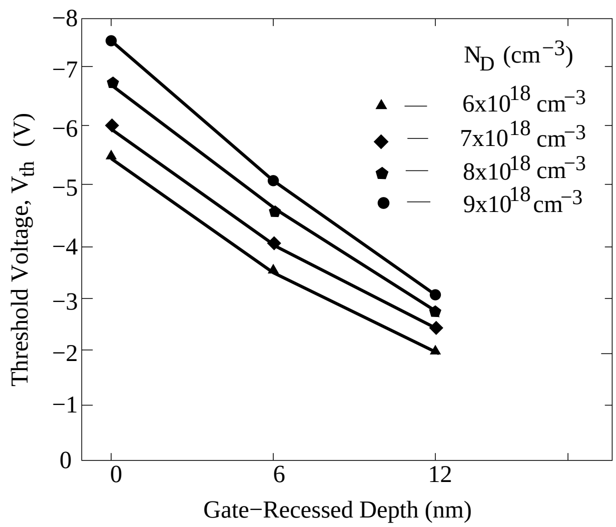

Figure 5: Threshold voltage variation with gate-recess for different doping concentration at V_{DS}=80V.

At a gate bias of 4V, the I_{ds} is found to be 2.3A/mm and 1.3A/mm for the device without and with 12nm gate-recess, respectively resulting a reduction of 44%. This is due to the fact that with the gate-recess, the gate is near to the channel which causes early pinch-off of the channel as compared to the device without gate-recess.

Fig. 5 shows the V_{th} variation as a function of gate-recessing in AlGaN/GaN/AlGaN DH-HEMT for different N_D. It is observed that the V_{th} decreases with increase in gate-recess depth at each doping level. Further, as N_D increases, the V_{th} also increases due to increase in I_{ds} and pinch-off takes place at higher gate bias.
The transconductance variation of the AlGaN/GaN/AlGaN DH-HEMT without and with 12nm gate-recess is shown in Fig. 6 at N_D=8x10^{-18} cm^{-3}. As seen, the transconductance enhances with

gate-recess structure. This indicates that the gate is having better control over the drain to source current when gate is recessed. The g_m of the device without and with 12nm gate-recess is found to be 265 mS/mm and 320 mS/mm at V_{DS}=80V. Thus, the simulation results show that a 12nm gate-recess AlGaN/GaN/AlGaN DH-HEMT provides a 20% increase in g_m as compared to the device without recess. The effect of gate recessing on g_m is shown in Fig. 7 for different N_D. It is observed that for a given gate-recess depth, the g_m of the device increases with increase in N_D. Therefore, it is clear from the trends of the curves of Fig. 5 and 7 that the designer has to make a trade-off between V_{th} and g_m while choosing a doping level of the AlGaN barrier layer.

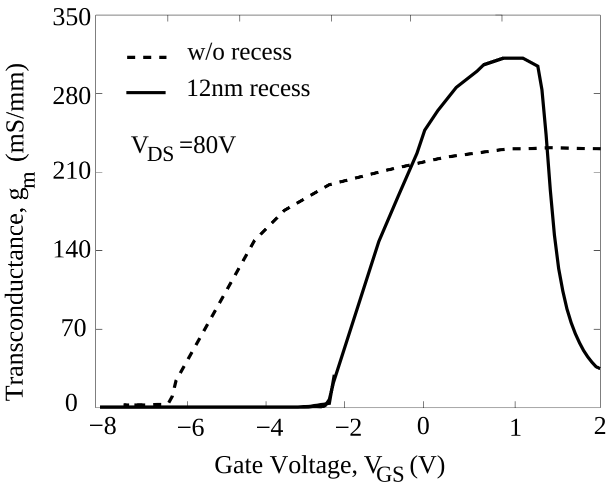

Figure 6: Transconductance curves of the AlGaN/GaN /AlGaN DH-HEMT without and 12nm gate-recess.

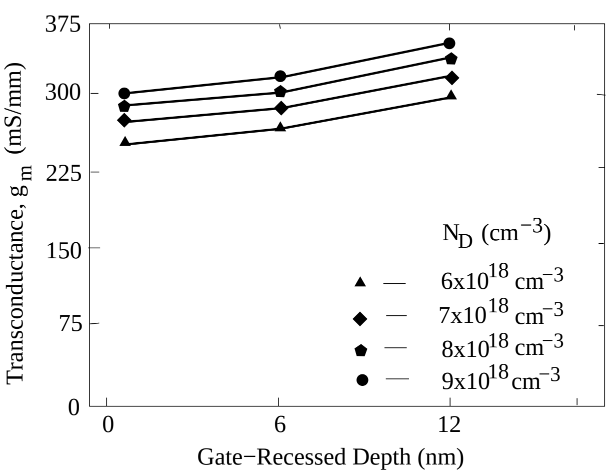

Figure 7: Transconductance variation with gate-recess for different doping concentration V_{DS}=80V.

Fig. 8 shows the breakdown characteristics of the AlGaN/GaN/AlGaN DH-HEMT without and with 12nm gate-recess. It can be seen that the breakdown voltage of the device drastically increases with gate-recessing. The V_{BR} is found to be 80V and 560V without and with 12nm gate-recess at N_D=8x10^{-18} cm^{-3} resulting seven times improvement in V_{BR}. This improvement in V_{BR} is due to reduction in electric field in the device as gate is recessed. The variation of V_{BR} with gate-recess for different N_D is given in Fig. 9. Thus, the increase in depth of the gate-recess enhances the breakdown voltage of the device while increasing N_D reduces the V_{BR}. This again indicates a trade-off between g_m and V_{BR} for doping of the AlGaN barrier layer.

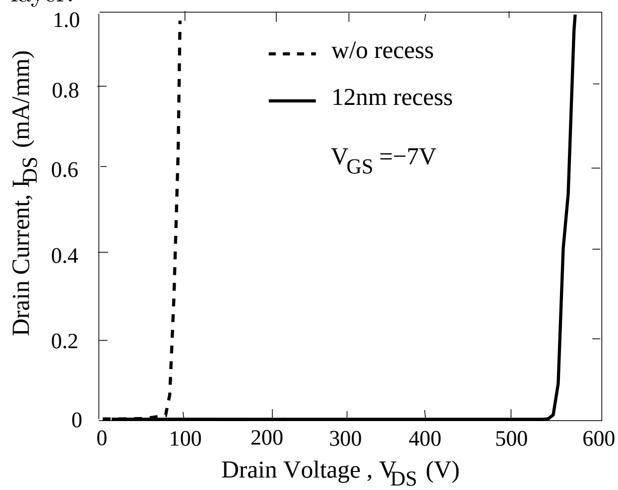

Figure 8: Breakdown voltage comparison of AlGaN/GaN/AlGaN DH-HEMT for without and 12nm gate-recess.

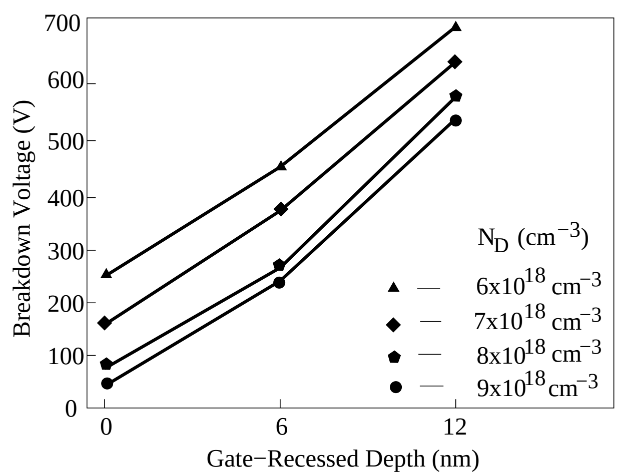

Figure 9: Breakdown voltage variation with gate-recess for different doping concentration (V_{GS} = -7 V)

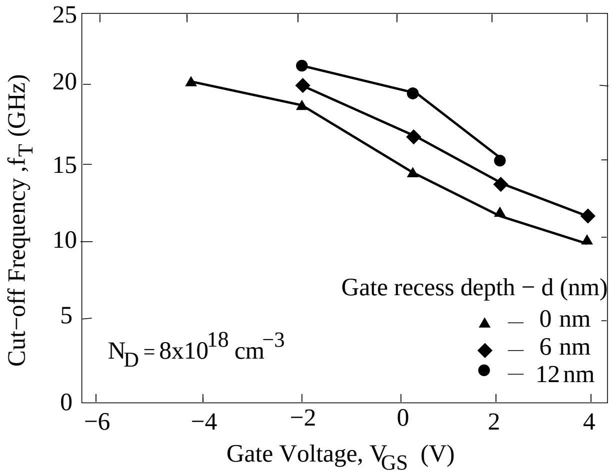

Figure 10: Cut-off frequency variation with gate voltage for different gate-recess at V_{DS}=25V

Fig. 10 provides the cut-off frequency variation with the gate voltage of the AlGaN/GaN/AlGaN DH-HEMT device for different gate-recess at N_D=8x10^{18} cm^{-3} and V_{DS}=25V. As seen, the f_T of the AlGaN/GaN/AlGaN DH-HEMT increases with gate recessing due to increase in g_m. At V_{GS}=0V, the f_T of the device is found to be 14 and 20 GHz for without and with 12nm gate-recess, respectively leading to 43% improvement in f_T.

5 Conclusion

In this paper, the AlGaN/GaN/AlGaN based DH-HEMTs are studied using 2D numerical simulations in the device simulator, ATLAS. The simulation results of a AlGaN/GaN/AlGaN DH-HEMT are compared with the reported experimental data. A good agreement between the simulated characteristics and measured data is obtained which confirms the validity of simulation results. The effects of gate-recessing and doping of the AlGaN barrier layer on the performance parameters of the AlGaN/GaN/AlGaN DH-HEMT structure with field-plate are studied. It is demonstrated that a significant improvement in threshold voltage (V_{th}), transconductance (g_m)), breakdown voltage (V_{BR}) and cut-off frequency (f_T) can be achieved by employing the gate-recess at the cost of reduction in the drain current (I_{ds}) of the device. The AlGaN/GaN/AlGaN DH-HEMT device is suitable for high frequency power applications such as military communication and navigation systems.

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