A Comparative Analysis of Analog Performance of an U-DG AlGaN/GaN MOS-HEMT Device with Hafnium based high-k dielectric as the gate oxide and an U-DG AlGaN/GaN Schottky-HEMT Device

Hrit Mukherjee #1, Rajanya Dasgupta #2, Mousiki Kar *3, Atanu Kundu *4

#*Department of Electronics and Telecommunication Engineering, Jadavpur University*
Kolkata, India
1hritmukherjee@gmail.com
2rajanya.dasgupta@gmail.com
**Heritage Institute of Technology*
Kolkata, India
3mousikikar@gmail.com
4kundu.atanu@gmail.com

***Abstract* — This paper elucidates a comparative and analytical study on the basis of analog performances of an Underlapped Dual Gate (U-DG) AlGaN/GaN MOS-HEMT with Hafnium based high-k dielectric (HfO_2) as the gate oxide and an Underlapped Dual gate AlGaN/GaN Schottky-HEMT. The study has been conducted based on the effect on the conduction band energy profile and also on the basic Analog Figures of Merits (FoMs) like Drain current (I_D), Transconductance (g_m), Output Resistance (r_o), Intrinsic Gain ($g_m r_0$), when the oxide layer of the MOS-HEMT is removed and a Schottky contact is made. Both these heterostructured devices show superior performance as power transistors due to enhanced efficiency, cost-effectiveness, better reliability and controllability over silicon based conventional DG-MOSFETs.**

Index Terms —Analog, AlGaN/GaN, carrier mobility, Drain Current, heterojunction, MOS-HEMT, Schottky-HEMT, Symmetric Underlap.

I. INTRODUCTION

In the past two decades, CMOS technology has rapidly embraced the field of electronic devices and circuits, providing low-power and high-speed performances, thereby rising to dominate the electronics industry. The secrets to this rapid development lie in the very basics of solid state semiconductor physics, one of them being the preference of using heterostructured devices over homostructured ones. While in semiconductor-semiconductor homojunctions, dopants are injected epitaxially/, these dopants stay scattered in the conducting channel, hindering the normal flow of the carriers by impurity scattering thus reducing mobility. Further, as millions and billions of devices need to be integrated on a single chip, all of them may not have the same threshold voltage and even a leakage current in the order of nanoamperes will thus lead to a huge power loss. To overcome these shortcomings, compound semiconductors are formed by combining two or more elements from different columns of the periodic table **[1].**

Since, traditional MOSFETs have been found to deliver slower performances owing to the impurity scattering in short channel devices, which eventually also gives rise to undesirable heating and loss**[2]**, growth of high-electron-mobility-transistor (HEMT) structures of graded aluminium gallium nitride–gallium nitride (AlGaN/GaN) is now preferred over the former **[3-5]**. Wide and tuneable band gap, high electron mobility and average drift velocity, high breakdown voltage as well as good thermal stability makes gallium nitride (GaN) a promising material for high power and high frequency electronic devices**[6].** Usually GaN-based electronic devices are fabricated on foreign substrates such as sapphire, Si, and SiC**[7].** However, AlGaN/GaN HEMT structures on high quality ammonothermal GaN substrate became recently available **[8]** allowing development of low leakage current electronic devices **[9].**

In HEMT, the mobile electrons from the conduction band of $Al_xGa_{(1-x)}N$ residing within the diffusion length diffuses into the lower lying energy states of the GaN conduction band. As a result, band-bending occurs which prevents the electrons from returning to the AlGaN crossing the potential barrier at the GaN/AlGaN interface. The electrons in the almost triangular potential well on the GaN side form a 2-dimenional electron gas(2DEG) since electrons here are confined to move in two dimensions only.**[10]**

Although in HEMT devices, ionized impurity scattering is prevented and carrier mobility is also increased, the gate leakage current and buffer leakage are important factors limiting its performance and reliability. Therefore, a Schottky contact can be made between the gate metal and the channel, and the potential of the channel can be varied by applying a voltage at the gate. The gate voltage changes the gate capacitance and turns on/off the device. Schottky contact produces an energy band discontinuity between the channel and gate contact, known as Schottky Barrier. It blocks the flow of electron from gate to channel and vice-versa, thereby reducing gate leakage. However, the use of a gate oxide as an insulator between gate and channel helps to improve gate contact forming a MOS-HEMT, further decreasing the gate leakage current and increasing the drain current **[11-13]**. Nevertheless, it partly reduces the transconductance because of a larger gate-to-channel separation**[14].** But MOS-HEMT devices still exhibit a gate leakage reduction of six to ten orders of magnitude compared to a Schottky barrier HEMT of similar design**[15].•**

In this paper, an Underlapped Dual Gate (U-DG) AlGaN/GaN heterostructured MOS-HEMT and a Schottky-HEMT has been analyzed and compared on the basis of their electrical characteristics and analog performance. The use of dual gates help improve the channel control and reduce the short channel effects(SCEs). They also add to higher on current (I_{on}) by better channel utilization**[16-17]**. Underlap creates a physical separation between Gate and Drain, suppressing DIBL and hence to reduce the off current (I_{off})**[18].**

II. Device Structure

The two dimensional cross sectional views of an U-DG AlGaN/GaN heterostructured MOS-HEMT and a Schottky-HEMT with symmetric source and drain overlap on both sides of the two gates are depicted in Fig. 1. and Fig. 2. respectively. While a rectifying contact is formed between the gate and the channel in the Schottky-HEMT, the MOS-HEMT uses Hafnium based high K dielectric gate material with thickness (oxo) 10 nm, to achieve improved device performance**[].**The device dimensions that are common to both taken into consideration is gate length (Lg) of 200 nm, underlap length on both sides of source/drain electrodes (L_s/L_d) of 200 nm, source/drain length (S) of 200 nm according to ITRS 2008 for RF and Mixed Signal applications **[19].** In both the devices, straddling (type I) type AlGaN/GaN heterojunction has been implemented with a layer of AlGaN of thickness (d) 18 nm grown over GaN with thickness (buf) 180 nm.Research shows that the I_{on}/I_{off} ratio, studied for a varying range of channel thickness, is maximum in the range 140 nm to 180 nm **[20]**. Therefore, in this paper, the Analog Figures of Merits have been studied for both the devices keeping the channel thickness as 180 nm.

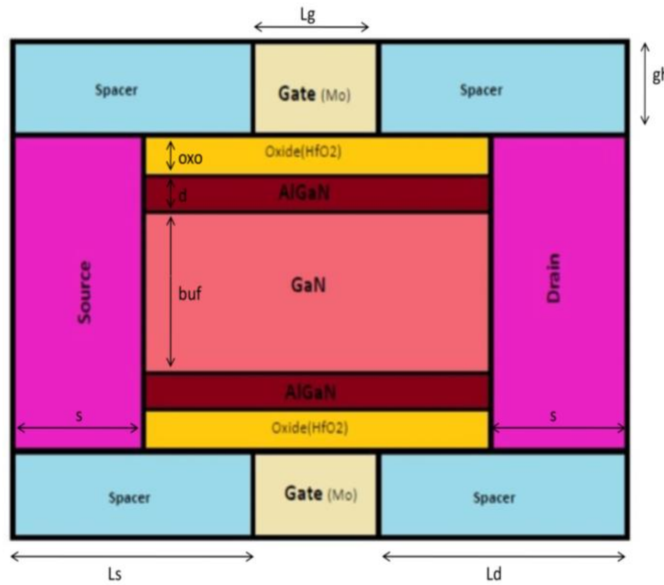

Fig. 1. Cross section of U-DG AlGaN/GaN MOS-HEMT with source and drain underlap.

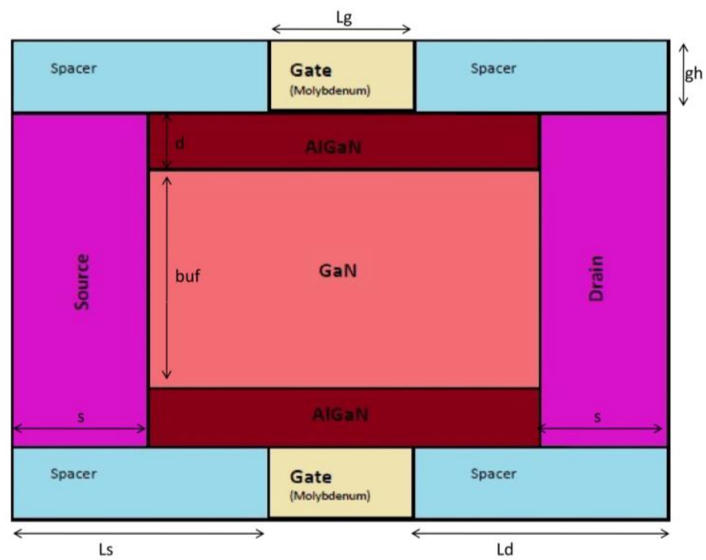

Fig. 2. Cross section of U-DG AlGaN/GaN Schottky-HEMT with source and drain underlap.

III. Simulation Procedure

All the simulations relevant to the analysis have been performed using TCAD-Sylvaco device simulator **[19]** and standard experimental data has been used for calibration **[21].** The model specifications have been adjusted and tuned for incorporating the attributes and features of this experimental prototype into the simulator model. Mobility models have been included to handle the effects of carrier mobility degradation owing to the short channel effects (SZEs) like surface scattering and carrier velocity saturation due to the high lateral electric field. The Albrecht Model is added to simulate low field mobility calibration in the device, the Shockley-Reed-Hall (SRH) Recombination Model is incorporated for determining the correct active carrier lifetime and the Fermi-Dirac statistics model for correct device processing. Polarization Model is for GaN based devices and Newton Model is for device computations involving complex equations and quadratic convergence. The mole fraction, x of Al in $Al_xGa_{(1-x)}N$ is considered as 0.3 with Molybdenum as the gate material and metallic source and drain having a work function of 4.31 eV on Si_3N_4 substrate. The following section showcases a comparative study of Analog Performances of the above described MOS-HEMT and Schottky-HEMT devices.

IV. Analog Performance

The Analog FOMs that have been compared between a MOS-HEMT and a Schottky-HEMT include the variation of Drain Current (I_D) with respect to both Gate to Source Voltage (V_{GS}) and Drain to Source Voltage (V_{DS}), Transconductance (g_m), Output Resistance (r_o) and Intrinsic Gain ($g_m r_o$).

Fig. 3. And Fig. 4. shows the variation of conduction band energy along the length of the channel for MOS-HEMT and Schottky-HEMT devices in OFF state and ON state respectively. As observed from the Fig. 4., both the devices have almost same conduction energy variation throughout the channel, in the central part of the channel beneath the gate together with the underlaps on either sides, the conduction band energy in MOS-HEMT is lower than that of Schottky-HEMT. This implies more number of carriers can overcome the barrier between source and channel and thus reach the drain, contributing to large drain current for any specific V_{DS}.

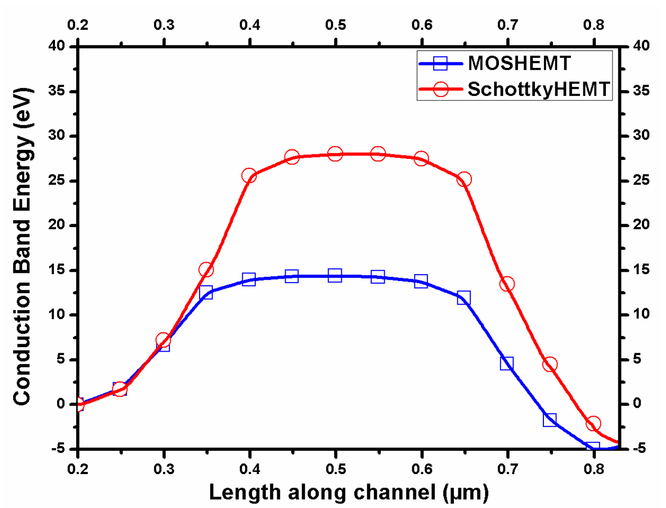

Fig. 3. Conduction band energy variation along the channel of U-DG AlGaN/GaN MOS-HEMT and Schottky-HEMT at V_{DS} = 5.0 V for an applied V_{GS} = -50 V, when both devices are in OFF state.

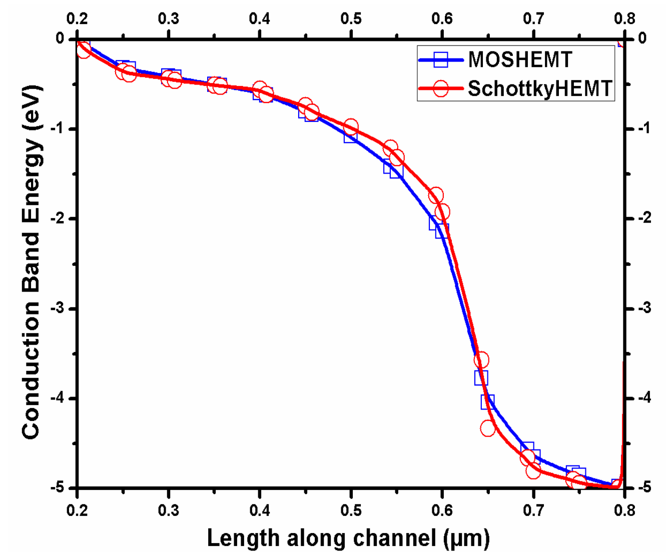

Fig. 4. Conduction band energy variation along the channel of U-DG AlGaN/GaN MOS-HEMT and Schottky-HEMT at VDS = 5.0 V for an applied VGS = 1 V, when both devices are in ON state.

Fig. 5. illustrates the variation of I_D with respect to V_{DS} and as it depicts, I_D is almost same in linear region for both devices, but in saturation region I_D for MOS-HEMT is higher and this difference keeps increasing with increasing V_{DS}. This fact can be justified by the above explanation which shows MOS-HEMT has lower conduction band energy than Schottky-HEMT in the channel, and hence I_D will be higher for MOS device for a particular V_{DS} in saturation region.

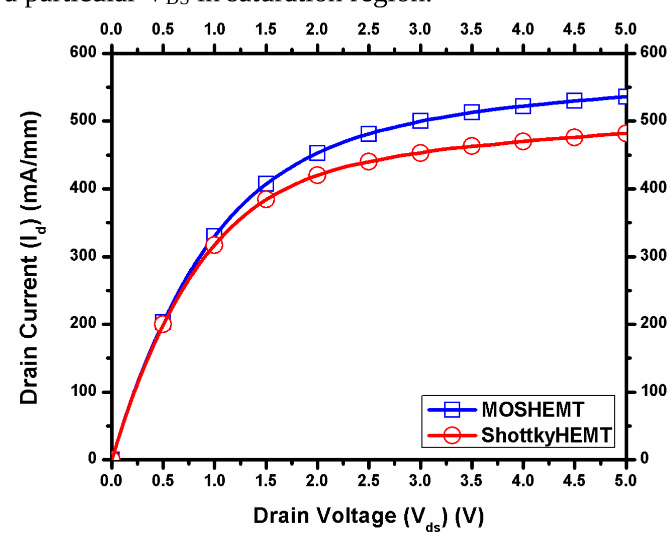

Fig. 5. Variation of I_D in linear scale as a function of V_{DS} at V_{GS} = 1.0 V for U-DG AlGaN/GaN MOS-HEMT and Schottky-HEMT devices.

In both the devices, a conduction channel is already present beforehand which enables current flow even at zero gate bias voltage. Increasing the gate bias voltage makes the channel further conducting, whereas, decreasing it drives the channel into cut-off. The negative gate voltage required to completely turn off the device is called threshold voltage, V_{th}. In Schottky-HEMT, V_{th} is the voltage required to fully deplete the doped channel region of the reverse biased Schottky junction, thereby removing the channel band bending at the gate/AlGaN interface. On the other hand, in MOS-HEMT, both the oxide band bending and the channel band bending have to be removed to turn off the device. Therefore, greater negative gate bias voltage is required for MOS-HEMT. So, absolute value of threshold voltage is greater for MOS-HEMT in comparison to Schottky-HEMT as is evident from Fig. 6.

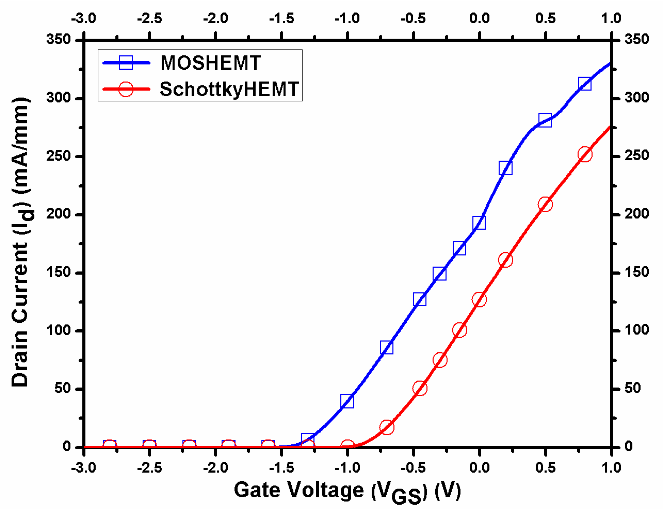

Fig. 6. Variation of I_D in linear scale as a function of V_{GS} at V_{DS} = 1.0 V for U-DG AlGaN/GaN MOS-HEMT and Schottky-HEMT devices.

In case of MOS-HEMT, the metallic oxide present between gate and substrate not only serves as an insulator by reducing the gate leakage current, but also increases the gate capacitance giving better gate control over channel thus accounting for improved device performance. As the charge stored per unit channel area, $Q_{ch} = C_{ox}(V_{GS} - V_{th} - V_x)$, where C_{ox} is the oxide capacitance per unit area and V_x is the channel potential at a distance x from source where x varies from 0 (source end) to $L_s+L_g+L_d$ (drain end), the concentration of charge carriers per unit channel width will be more in MOS-HEMT than Schottky-HEMT due to the presence of C_{ox} term. Thus, as evident from Fig. 6., I_D of MOS-HEMT is greater than Schottky-HEMT for any specific V_{GS}.

Fig. 7. illustrates the transconductance curves for both MOS-HEMT and Schottky-HEMT with varying V_{GS}. Mobility degradation due to surface roughness scattering at the oxide channel interface under high vertical effective fields causes the transconductance to exhibit a fall-off at about 0.5V above threshold in conventional MOSFETs **[22]**. However, Schottky experiences higher carrier mobility in the channel as compared to MOS. This is because the carriers located in the inversion layer of the MOS have a wavefunction extending into the oxide which causes their surface mobility to drop than that of the bulk material. On the other hand, as the depletion layer in Schottky separates the carriers from the surface their mobility is close to the bulk material **[23]**. Lower mobility leads to lower transconductance. But since I_D is higher in MOS and the threshold is also more negative, the g_m-V_{GS} curve of MOS-HEMT starts at lower V_{GS}, increases and experiences an early fall off at a higher rate than that of Schottky and therefore a cross-over is observed of both the curves at approximately -0.5V after which the transconductance of Schottky always leads that of MOS.

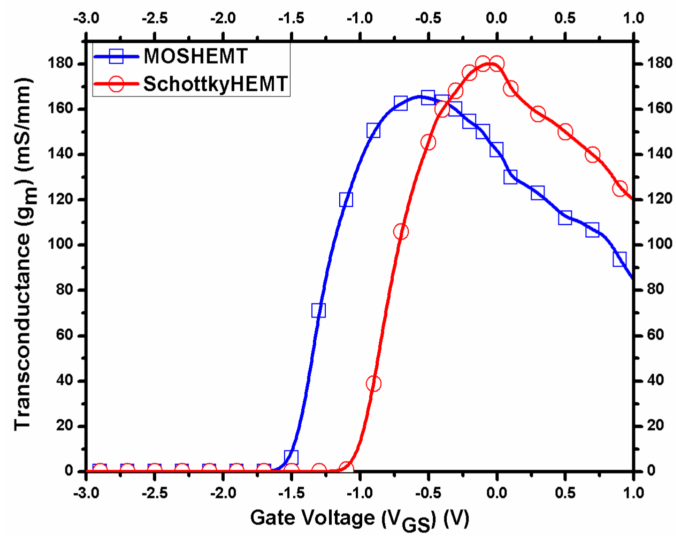

Fig. 7. Variation of g_m in linear scale as a function of V_{GS} at V_{DS} = 1.0 V for U-DG AlGaN/GaN MOS-HEMT and Schottky-HEMT

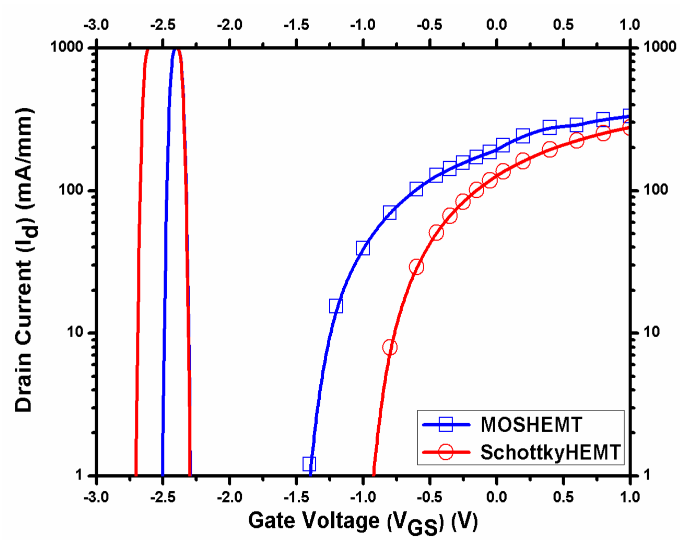

Fig. 8. Variation of g_m in logarithmic scale as a function of V_{GS} at V_{DS} = 1.0 V for U-DG AlGaN/GaN MOS-HEMT and Schottky-HEMT

It is observed from **Fig** , output resistance, r_0 of Schottky-HEMT is higher than that of MOS-HEMT. This can be justified by the fact that since, the drain current in MOS is higher than that of Schottky because of the presence of the gate oxide layer which provides better control to the channel, change in drain current for same change in drain voltage in saturation is also higher in MOS, yielding lower r_o in MOS-HEMT, compared to Schottky-HEMT.

The g_m and r_o values thus obtained illustrate the plot of intrinsic gain with V_{GS} in Fig. 10. An expected curve similar to that of g_m/V_{GS} plot is obtained but multiplied by a constant factor, r_o of each device.

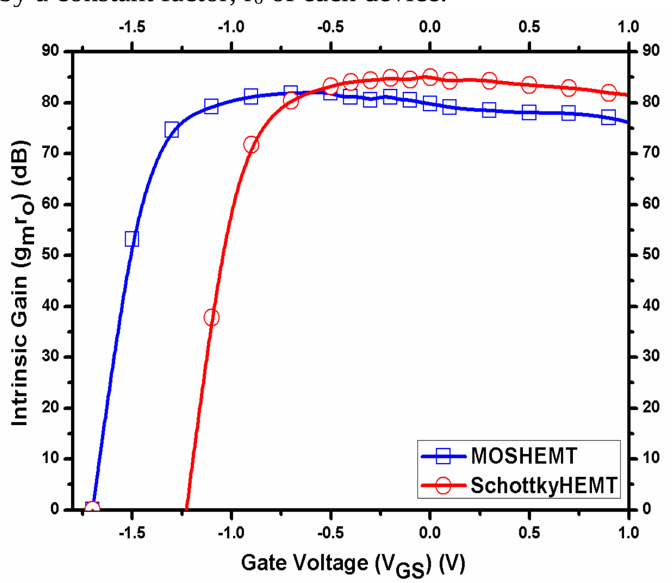

Fig. 10. Variation of $g_m r_o$ in linear scale as a function of V_{GS} at V_{DS} = 1.0 V for U-DG AlGaN/GaN MOS-HEMT and Schottky-HEMT

V. Conclusion

The simulation results indicate that Schottky HEMT provides relatively lower ON currents as compared to MOS HEMT structures and thus can be more useful when it comes to low power consuming high performance devices and also economical as Schottky-HEMTs undergo only a two step photolithography processing procedure as oxide layer implantation is not required. But the greatest disadvantage is that turn-on voltage for Schottky is very low and since, the threshold has to be lower than the turn-on voltage, MOS-HEMTs are preferred more in high voltage applications. It was further provided with double gates and underlap both of which reduces the short channel effects to a great extent. Hence, from a futuristic point of view, these HEMT structures could be proposed as a replacement to conventional MOSFETs.

VI. Acknowlefgemwnt

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