Physics based simulation for studying the impact of contact resistance on DC & RF characteristics of AlGaN/AlN/GaN HEMT

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Abstract— **Formation of a two-dimensional electron gas (2DEG) in AlGaN/AlN/GaN heterostructures plays a vital role in high power and high frequency device technology. Such kinds of heterostructures are used for the fabrication of High Electron Mobility Transistors (HEMTs). Ohmic contacts to AlGaN/AlN/GaN based heterostructures with low contact resistance and smooth surface are crucial in the development of high power, high frequency transistors in the GaN system. In the present study, physics based simulation of impact of ohmic contact resistance on DC and RF characteristics of AlGaN/AlN/GaN HEMT on 6H-SiC substrate has been addressed for the first time. Three samples, A, B and C of contact resistance 0.25, 0.27 and 0.59 □*mm respectively were fabricated with different process variations. By using measured contact resistance values, physics based simulation of 100nm gate length GaN HEMT was done and corresponding device behavior was studied using TCAD. It has also been shown that simulated results for AlGaN/AlN/GaN heterostructure are closely matching with reported measured data.**

Index Terms— **GaN HEMT, ohmic contact, contact resistance, simulation, TCAD**

I. INTRODUCTION

WIDE band gap (WBG) semiconductors, like Gallium Nitride (GaN) and Silicon Carbide (SiC) are considered the most promising materials for the next generation high power and high frequency applications. In comparison to Si and GaAs the extraordinary physical properties of WBG, particularly III nitrides, such as a wide band gap, a high critical electric field, high mobility and saturation velocity, give the possibility to fabricate devices operating at much higher voltages, temperatures and frequencies. Further, devices fabricated using WBG materials show significant increase in energy efficiency and reduction in power losses. AlGaN/AlN/GaN based HEMTs have found a special place in communication systems due to the above distinct advantages. The AlGaN/GaN based heterostructure with AlN as spacer layer exhibits promising DC and RF performance for HEMT due to reduction in alloy disorder scattering. Presence of AlN as spacer layer plays a vital role in suppressing carrier penetration from GaN into AlGaN barrier layer [1-3]. However, in AlGaN/AlN/GaN based HEMTs, insertion of AlN spacer layer results in increase in potential barrier height in ohmic contact region which leads to a significant increase in the contact resistance (Rc) [4, 5]. Increase in contact resistance impacts current flow from 2DEG in GaN channel to source and drain electrodes. Chemical inertness and thermal stability of AlGaN/AlN/GaN also engender difficulties in ohmic contact formation. To achieve high current densities and high extrinsic gains, which are required to obtain high thermal stability and high DC and RF performance of devices, low-resistance ohmic contact is essential for HEMTs [6, 7]. In this context, ohmic contacts in GaN based HEMT fabrication are considered as a fundamental building block of power devices, as they provide link of the device to external circuits. In order to minimize device on-resistance (Ron), knee voltage (Vknee) and hence power losses, ohmic contact resistance must be negligible with respect to that of the semiconductor layer. Hence, it is desirable to predict device performance prior to fabrication through precise simulation and modeling. In this paper we have demonstrated physics based simulation of GaN heterostructure and HEMT device using Silvaco® TCAD. Appropriate physical models and physical mechanisms inherent in GaN heterostructure were taken into account and thereby ensuring well-converged solutions with consistent simulation results. In the present study three samples A, B and C of contact resistance 0.25, 0.27 and 0.59 □*mm respectively were fabricated with different process technologies namely recess etching of barrier layer and surface plasma treatment. Physics based device simulation of GaN HEMT corresponding to different contact resistance values was done and corresponding device behavior was explained using

TCAD. AlGaN/AlN/GaN heterostructure was simulated and material properties were extracted in terms of polarization charge, mobility, 2DEG concentration, conduction band energy profile etc. Using this heterostructure, GaN HEMT device performance was extracted in terms of DC and RF characteristics. Simulated device performance was compared with corresponding reported measured data and showed good agreement.

II. DEVICE DESCRIPTION AND PHYSICAL MODELS

In this study, MOCVD grown AlGaN/AlN/GaN based heterostructure on 6H-SiC substrate procured from M/s. Seen Semiconductors, Poland was used for fabricating samples. Heterostructure consists of 60nm AlN nucleation layer, 2µm thick undoped GaN channel layer, 1nm AlN spacer layer, 20nm undoped Al0.3Ga0.7N barrier layer and 3nm Si3N4 passivation layer as shown in figure 1. Three samples were prepared, two with different recess etching and one with surface plasma treatment process for ohmic contact fabrication. Standard Transmission Line Method (TLM) patterns were defined by photo-lithography as shown in figure 2 with separations varying from 3 to 36 microns. The current-voltage (I-V) characteristics of the TLM contacts were measured using semiconductor characterization system at room temperature. Contact resistance, specific contact resistance and sheet resistance were computed through transmission line method measurements on metal contacts.

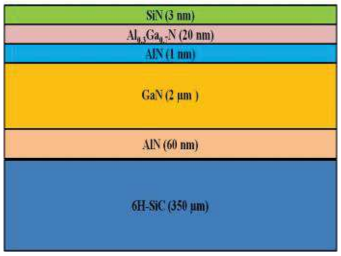

Fig. 1. AlGaN/AlN/GaN based heterostructure

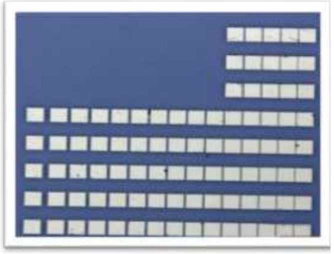

Fig. 2 Optical image of TLM pattern after metal lift-off

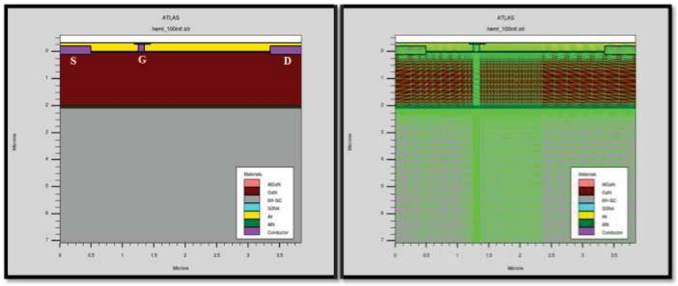

Fig. 3(a) The cross-sectional view of simulated GaN Heterostructure (b) Meshed GaN Device

TABLE I

SUMMARY OF OHMIC CHARACTERISTIC OF THE THREE SAMPLES

Sample Id	CR (Ω*mm)	SR (Ω/□)	SCR (Ω* cm2)
Sample A	0.25	184	3.40 E-6
Sample B	0.27	267	2.90 E-6
Sample C	0.59	368	9.26 E-6

CR = Contact Resistance, SR = Sheet Resistance, SCR = Specific Contact Resistance.

Summary of ohmic characteristic of three samples is given in Table 1. In this study, we have performed Atlas device simulation of GaN HEMT devices with 100 nm gate length. The spacing between source and gate electrode is 0.75 µm and spacing between gate and drain electrode is 2 µm. The geometry of gate is considered as T-gate structure for simulation, as this enables to lower the gate-resistance by its increased cross-sectional area. Such gate-structure with gate-head on the drain side serves as a field-plate and can increase the breakdown voltage. The cross-sectional view of simulated GaN heterostructure and meshed GaN HEMT device are shown in Figure 3 (a) and 3 (b) for 100nm gate length. A computation mesh is required for the simulation routine. Fine meshing is defined at metal/semiconductor junctions, AlGaN/AlN and AlN/GaN interfaces, in the region under the gate and on the edges of the source and drain contacts in order to increase the convergence and accuracy of the calculations. Convergence difficulties in this simulation generally arise due to formation of large polarization charges, sudden change in defining mesh structure, use of abrupt heterojunctions with a Schottky gate. Suitable physical models and mechanisms for GaN heterostructure were taken into account and thereby confirm well-converged solutions with stable simulation results. In simulation, basic equations of physical processes were solved for every grid point. These equations include Poisson's equation, continuity equations, and transport equations, derived from Maxwell's equations [12]. The computation of 2DEG due to polarization effect was performed during the simulation using polarization model [13]. For AlGaN/GaN Ga-face HEMT devices, the 2DEG comes from spontaneous and piezoelectric polarization induced positive charge at the AlGaN/GaN interface, which pulls the conduction band down to the Fermi level, and does not require dopants as for example in AlGaAs/GaAs devices. Additionally, there are strong polarization fields in the AlGaN/GaN material system (spontaneous and piezoelectric polarization). Failure to include this strong polarization field will introduce distortion to the calculated band diagrams and thus compromise simulation results. The source and drain electrodes form ohmic contacts to the 2DEG by setting their work function identical to the electron affinity of the AlGaN layer. The gate forms a Schottky contact to the AlGaN layer. Specific physical models and material parameters were considered to take into account the mole fraction of AlGaN/GaN system [13]. Low field mobility was modeled using the Albrecht et.al [14] model, allowing the separate control of electrons and holes. Shockley-Read-Hall Recombination was used to estimate the statistics of production of holes and electrons and their recombination through the phenomenon of trapping. Performance of GaN device and convergence of its simulation was significantly influenced by the presence of defects. Accordingly, we also introduced interface traps in this simulation based on measurement results using DLTS (Deep Level Transient Spectroscopy). Threshold voltage and substrate leakage current were controlled by a concentration of acceptor and donor traps in the GaN buffer layer, respectively. Moreover, we put the interface traps to represent Fermi level pinning at the bottom of the GaN buffer. It should be noted that these traps play an important role in the convergence of the device simulation.

III. RESULTS AND DISCUSSIONS

2D ATLAS device simulator was used to analyze the device under consideration to achieve accuracy and good computational efficiency. AlGaN/AlN/GaN heterostructure as shown in Figure 3 (a) was simulated and device structure was defined. The simulator solved a system of partial differential equations as mentioned earlier and DC and RF characteristics of the device were simulated with different measured contact resistance values i.e. 0.25, 0.27 and 0.59Ω*mm.

Output characteristics of the device corresponding to 0.25, 0.27 and 0.59 Ω*mm contact resistance values are shown in Figure: 4 (a), 4 (b) and 4 (c) respectively. The output characteristic was simulated between drain current density (Ids) and drain voltage (Vds) with gate bias step from 0V to -2V and drain bias was ramped from 0 V to 16 V. The inference from output characteristic is that maximum drain current density (Idss) obtained corresponding to sample A, B and C is 0.995A/mm, 0.98A/mm and 0.88A/mm respectively at Vgs=0V. It clearly demonstrates that higher the contact resistance, lower is the drain current density. It is known that RF output power of a transistor is directly proportional to maximum drain current density (Idss). So increasing Idss is a critical parameter for high power applications. Other important parameter which was extracted from output characteristics was knee voltage (Vknee). The inference from output characteristic is that Vknee obtained corresponding to sample A, B and C is 5V, 5.1V and 6.3V respectively at Vgs=0V. It clearly demonstrates that higher the contact resistance, higher is the knee voltage. It is desirable to get low knee voltage for good DC and RF performance of device. RF output power can be expressed in terms of knee voltage as following [15]

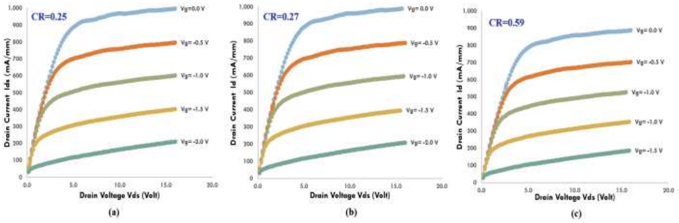

Fig. 4(a) Output Characteristics of Sample A, (b) Output Characteristics of Sample B and (c) Output Characteristics of Sample C

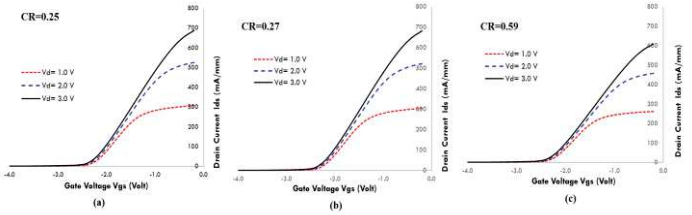

Fig. 5(a) Transfer Characteristics of Sample A (b)Transfer Characteristics of Sample B (c) Transfer Characteristics of Sample C

$$\text{Pout} = \frac{1}{8} * \text{Idss} * (\text{Vbreakdown} - \text{Vknee}) \qquad (1)$$

Equation (1) clearly indicates requirement of smaller knee voltage to achieve high output power. It is important to obtain Vknee as low as possible in order to get as large current/voltage excursion as possible. Simulated output characteristics also indicate strong depletion type characteristics of the HEMT device. Another parameter extracted from output characteristics was on resistance (Ron). The inference from output characteristic is that Ron obtained corresponding to sample A, B and C is 3.5, 3.6 and 4.5 Ω*mm respectively at Vgs=0V. It clearly demonstrates that higher the contact resistance, higher is the on resistance. It is desirable to get low on resistance in order to minimize the power losses of the system. Lower on-resistance is also crucial for switching applications. Figure 5 (a), 5 (b) and 5 (c) represents the transfer characteristic between gate to source voltage (Vgs) and drain current (Ids) for different drain voltages (Vds) varying from 1 to 3V. From transfer characteristics, threshold voltage for sample A, B and C are -3.0V, -2.8V and -2.6V respectively. Figure 6 depicts transconductance characteristics corresponding to sample A, B and C for different gate voltages ramped from −4 V to 0 V at Vds=3V. The maximum transconductance values obtained for sample A, B and C are 384 mS/mm, 381 mS/mm and 333 mS/mm respectively. As the cut-off frequency is directly proportional to the transconductance, higher value of gm will enable to achieve higher cut off frequency. When using the device in high speed circuitry, current gain cut-off frequency and maximum frequency of oscillations (fmax) are two most pertinent parameters. Cut off frequency (ft) and maximum frequency of oscillations (fmax) were extracted from small signal RF simulation. Current gain (h21) and maximum

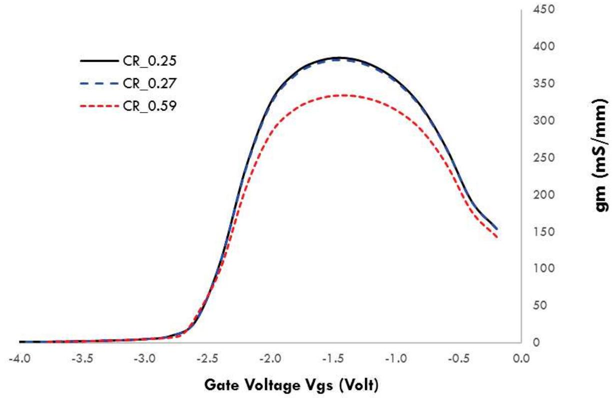

Fig. 6: Trans conductance of Sample A, B and C at Vds=3.0 V.

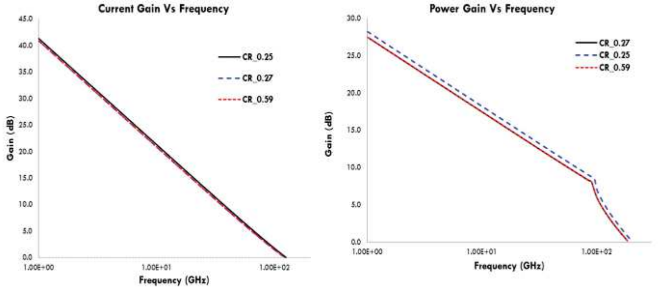

Fig. 7(a) cut-off frequency of Sample A, B and C; (b) maximum frequency of Sample A, B and C available power gain (Gam) were simulated at bias conditions Vds=7V & Vgs= -1.5V and plotted with respect to frequency in Figure 7 (a) and 7 (b) respectively for sample A, B and C. It was observed that ft for sample A, B and C is 110GHz,110GHz and 105GHz respectively and fmax is 180GHz, 175GHz and 160GHz respectively. It clearly shows that higher the contact resistance lower are ft and fmax values. Summary of DC and RF device parameters corresponding to sample A, B and C are given in Table 2. In Table 2 we have shown corresponding reported measured values for AlGaN/AlN/GaN based heterostructure which are closely matching with our simulated results.

TABLE II
SUMMARY OF VARIATION IN DC AND RF DEVICE PARAMETERS

	Sample A	Sample B	Sample C	Reported Measured Value
Idss (A/mm)	0.995	0.980	0.880	1.2 [16]
Vknee (V)	5	5.1	6.3	4.75 [18]
Ron (ohm*mm)	3.5	3.6	4.5	3.5 [17]
Vth (V)	-3.0	-2.8	-2.6	-4.0 [16]
gm (mS/mm)	384	381	333	350 [16]
ft (GHz)	110	110	105	111 [16]
fmax (GHz)	180	175	160	183 [16]

IV. CONCLUSION

In this study, three samples, sample A, B and C were fabricated with different process variations and corresponding measured contact resistance values were analyzed using TCAD to evaluate impact of contact resistance on performance of AlGaN/AlN/GaN based HEMTs on 6H-SiC substrate. DC and RF characteristics of AlGaN/AlN/GaN HEMT were simulated using TCAD. Different DC and RF performance parameters were extracted for all three fabricated samples of different contact resistance values. It was observed that higher value of contact resistance degrades DC and RF performance of device. Simulated results were compared with reported measured data and showed close match with measured values. Based on the simulation results ohmic contact fabrication process can be optimized prior to device fabrication in order to achieve low contact resistance and optimal device performance. Hence it is inferred that device simulation allows users to speed up the product design process and shorten the development cycle. Physics based simulation allows prediction of behavior of real devices with different heterostructures and different device geometries, and reduces time and cost associated with development of devices.

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