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Characterization of Enhancement AlInN/GaN Hemts using Partial P-Type GaN Gate

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Abstract. This work attempts to characterize the Enhancement mode (E-mode) AlInN/GaN HEMT devices implemented using p-GaN gate for getting positive threshold voltage (Vt). The device channel consists of a lattice-matched wideband **Al0.83In0.17N** and narrowband GaN layers, along with p-GaN layer below the E-mode device. The 2D Sentaurus TCAD simulation is done using the hydrodynamic model. The simulation model is calibrated with the initially published experimental result. A comprehensive, quantitative investigation of transfer characteristics, transconductance, gate capacitance, gate leakage and RF gain for E-mode devices is done. The E-mode device exhibit a Vt of + 1.0 V. This new device exhibit almost similar transconductance characteristics. The E-mode device shows lower off-state leakage current, higher ION/IOFF ratio and lower SS. These results demonstrate the feasibility for fabricating an E-mode AlInN/GaN HEMT device which is extremely desirable for high speed and high-frequency applications.

Keywords- Enhancement mode (E-mode), HEMT, p-GaN, AlInN/GaN

I. INTRODUCTION

The AlInN/GaN heterostructures is based on High Electron Mobility Transistors (HEMTs) and metal oxide semiconductor HEMTs (MOS-HEMTs) [1-4]. By virtue of lattice matching in the AlInN/GaN structure, the devices show better performance than conventional AlGaN/ GaN heterostructure devices. AlInN/GaN devices offer higher spontaneous polarization induced two-dimensional electron gas (2DEG) density [5], higher drain current, stress-free structure with enhanced reliability, and higher thermal and chemical stability [3]. $Al_xIn_{1-x}N$ with Al composition of about 0.83 is nearly lattice-matched to GaN. The lattice matched AlInN/GaN devices have exhibited very high electron mobility (1200 to 2000 cm^2/Vs) and high 2DEG sheet carrier densities (3.2x10 $^{13}cm^{-2}$) [7,8]. Considering the immense potential of AlInN/GaN hetrostructure it has used in the current work.It’s reported a new approach in fabricating E-mode AlGaN/GaN HEMTs based on fluoride-based plasma treatment of the gate region in AlGaN/GaN HEMTs and post-gate rapid thermal annealing [9]. Masahito presented details of E-mode GaN MIS-HEMT device showing high drain current and complete enhancement-mode operation [10]. Fabrication of E-mode GaN/AlGaN HEMTs on SiC substrates achieved with high threshold voltage through the combination of low-damage and controllable dry gate-recessing and the annealing of the Ni/Au gates [11]. InP-based InAlAs/InGaAs E-mode HEMT's using non alloyed ohmic contacts and Pt-based buried-gate technologies, to reduce the source resistance (*RS*) [12]. A low R_{on} and high-breakdown-voltage E-mode AlGaN/AlN/GaN HEMT was fabricated [13]. Although there are many reported E-mode devices, the AlInN/GaN based e-mode device using p-GaN gate not yet explored. Thus, we have done the characterization of E-mode AlInN/GaN HEMT device implemented using p-GaN gate.

A lot of work has already been done in AlInN/GaN based HEMTs and MOS-HEMT devices, but it mostly focus on depletion mode devices [13]. As these devices are having negative threshold voltage (V_t), their deployments in digital switching applications is limited despite of having high speed switching characteristics even at very low device dimensions [11,12,13]. The E-mode AlInN/GaN may prove to be excellent device for high speed digital applications. Therefore, the analysis of AlInN/GaN based E-mode using p-GaN gate device would be a significance to predict accurately its potential for high speed and high-frequency switching applications.

Thus, in this paper for the first time, we report the analysis of AlInN/GaN based E-mode using p-GaN gate low device dimensions.

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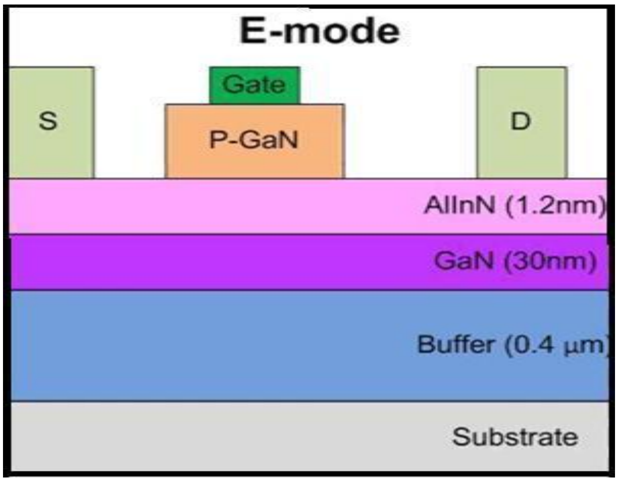

Fig. 1 Structure of Enhancement Mode AlInN/GaN HEMTs using partial p-type GaN Gate. The channel consists of intrinsic narrow band-gap GaN (30 nm) region and intrinsic wide and-gap $Al_{0.83}In_{0.17}N$(1.2 nm)

II. DEVICE DESCRIPTION

We have done the simulation study to analyze the performance of Enhancement- Mode AlInN/GaN HEMTs using partial p-type GaN gate (Fig 1). The devices have the gate length of 200 nm. The gate of E-mode device is built on top of 400 nm length p-GaN layer. The gate to source (L_{gs}) and gate to drain distance (L_{gd}) are kept fixed at 600 nm and 2000 nm. The source/drain region lengths are kept 50nm, with high doping of $10^{20}cm^3$ and an abrupt doping profile is introduced at source and drain ends. The gate consists of Ni/Au metal, having 1µm width for both devices. Source and drain contact resistance of *RC*=600Ω-µm included in simulation. The AlInN and GaN layers are intentionally kept intrinsic to minimize the scattering induced mobility degradation. The channel is formed at the interface of narrow bandgap GaN layer (30nm) and wide bandgap AlInN barrier layers (1.2 nm).The Physical properties of wide bandgap $Al_{0.83}In_{0.17}N$ and narrow bandgap GaN are listed in table 1.

Table 1 Physical properties of Al0.83In0.17N and GaN

Material	GaN	$^{Al}0.83^{In}0.17^{N}$
Eg (eV)	3.4	4.7
CBO (eV)	0.57	-
VBO (eV)	0.73	-
εo	9.5	11.7
Lattice Constant (A)	3.186	3.190
µe (cm^2/Vs)	940	1540
µh (cm^2/Vs)	22	82

III. SIMULATION MODEL CALIBRATION AND EXPERIMENTAL COMPARISON

Now we have simulated the previously published AlInN/AlN/GaN Gate-Recessed Enhancement-Mode HEMT device by Wang for calibrating the simulation model. The simulated transfer characteristics are compared with the intialy published transfer characteristics. The model parameters are tuned & adjusted for achieving a close matching between simulation and experimental transfer characteristics. Once a close matching is achieved, the simulation model is applied for simulating the proposed Enhancement Mode AlInN/GaN HEMTs Using partial p-type GaN Gate device**.**

The 2D simulations are done using HD model of TCAD device simulator G2012.06. This model accurately considers the non-equilibrium conditions such as quasi-ballistic transport and velocity overshoot effect. The physical effects such as bandgap narrowing, variable effective mass, and doping dependent mobility at high electric fields are also considered. For high speed devices the electron can attain high energy and the resulting transport,

For considering spontaneous polarization occurring in the AlInN/GaN heterostructure device fixed charges (n_{sp}) as listed in Table 3 are initiated at each interface. Effects of non-uniform distribution of the trapped electrons in the same direction horizontaly with the interface are also considered for the simulation, as the current continuity equation and Poisson equation are solved self-consistently. The $Al_{0.83}In_{0.17}N$ /GaN heterostructure is stacked along C-axis.

Table 2 Parameters are necessary to compute the temp. and electron mobility of Al0.83In0.17N.

Parameter	Value
Amin [$cm^2V^{-1}s^{-1}$]	75.9322
αm	2.1894
Ad [$cm^2V^{-1}s^{-1}$]	5204.361
αd	-3.2933
AN [cm^{-3}]	2E+17
αN	7.365
Aa	0.40252
αa	-0.20567

Table 3 Polarization charge density at each interface

Material	nsp(GaN)(cm^{-2})	nsp (AlInN)(cm^{-2})	Total (cm^{-2})
AlInN/GaN	-1.81 x 10^{13}	4.54 x 10^{13}	2.73x10^{13}
Al2O3/AlInN		- 4.54 x 10^{13}	-4.54 x 10^{13}

There is a considerable matching between the experimental and simulation transfer characteristics (Fig 2), validating the approximation of the carrier transport model and other model parameters used in the simulation model.

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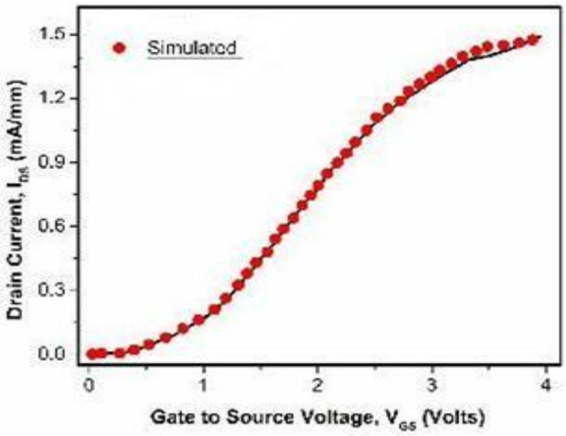

Fig. 2 Experimental (solid lines) and simulated (symbols) transfer characteristics for Gate-Recessed Enhancement-Mode InAlN/AlN/GaN HEMT

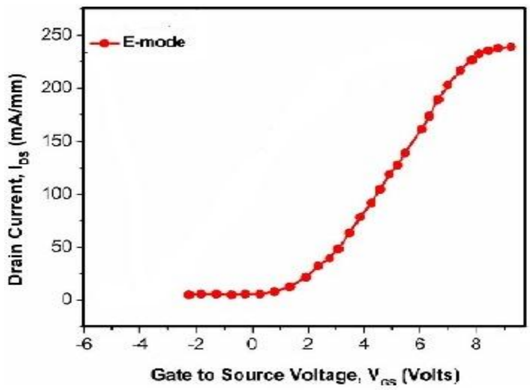

Fig. 3 ID-VDS characteristics for E-mode devices at applied drain voltage vds = 5v

IV. RESULTS AND DISCUSSION

The transfer characteristics for E-mode HEMT device shows excellent control of gate throughout the range. The measured V_t for E-mode devices was +1.0 v approximately. The stacking of 40nm p-GaN helped in achieving a V_t shift of 4.7V approximately. The V_t shifting is caused due to the carrier depletion in the channel below the p-GaN layer. The depletion of carriers in the channel area results in E-mode operation. The maximum drain current observed was 241 mA/mm E-mode devices. The E-mode devices exhibits better off-state performances.

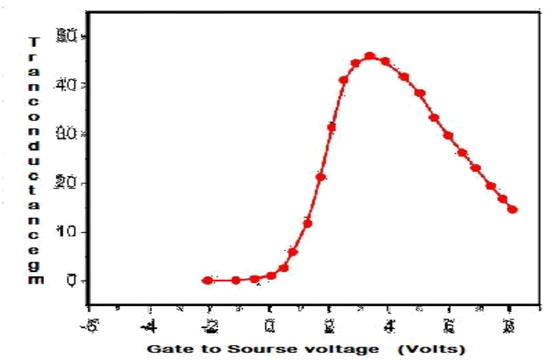

Fig. 4 Extrinsic gm as function of gate voltge for E-mode devices at applied drain voltage vds = 5v

Fig. 4 shows the transconductance (g_m) as a function of the gate voltage. Transconductance can be obtained from the ratio of variation in I_d to the variation of gate voltage (V_{gs}), for constant drain voltage (V_{ds}). The peak extrinsic $g_{m,max}$, observed was 46.1 mS/µm for E-mode device. The gate voltage swing (GVS) can be defined as the 10% drop from $g_{m,max}$, is about 1.7 V for E-mode device. Broader g_m profile are desirable as broader profile provides an improved linear behavior from which a smaller intermodulation distortion, its a smaller phase noise and a sufficient dynamic range could be expected.

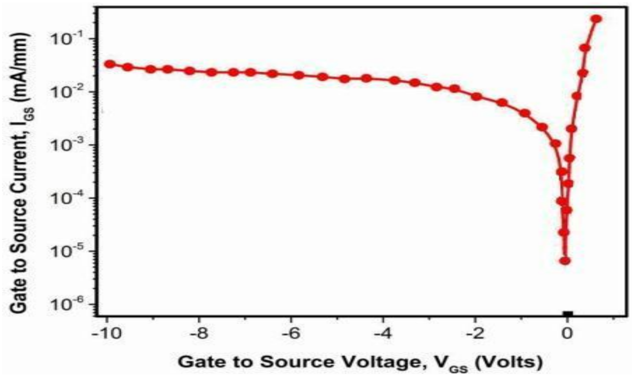

Fig 5 Dependence of Gate to Source current on gate to source voltage for E-mode device.

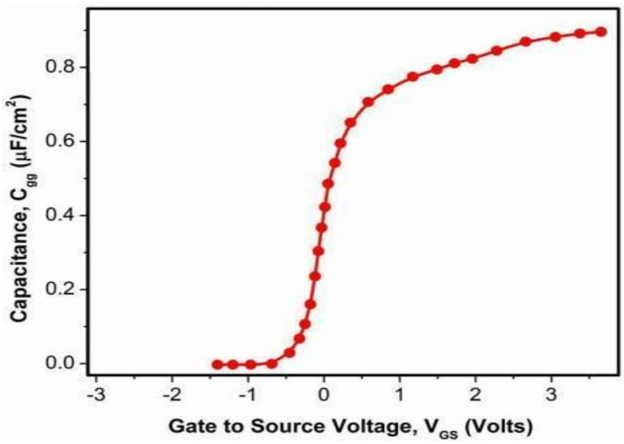

Fig 6 Capacitance as a function of gate voltage for E-mode device at 1MHz freq.

Fig 5 represents the logarithmic scale of gate leakage current as a function of V_{gs} gate-to-source voltage. Both devices exhibit excellent off-state performances such as I_{off} leakage and low SS. The E-mode device has a very low

I_{off} leakage of 5.4 x 10^{-7} mA/mm at Vgs= 0 V, high I_{on}/I_{off} ratio of 3x10^8 and low SS of 132 mV/decade

The capacitance versus voltage (C-V) simulations for E-mode The AC analysis was performed to extract C-V curves at 1 MHz frequency. The C-V measurements

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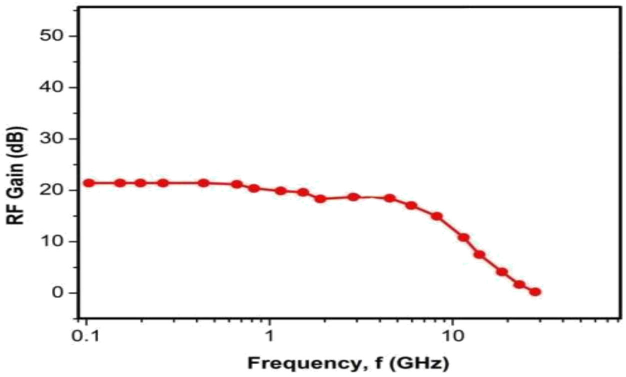
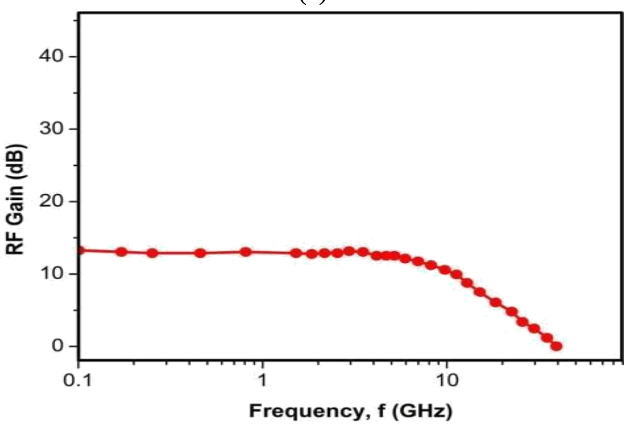
shows negligible hysteresis. The V_t shift for E-mode device can also be observed from C-V measurement.



(a)



(b)

Fig 7, RF characteristics of E-mode device

The E- device is of significance for high-speed digital applications and higher f_{max} corresponds to the Ft at P_{max} available which is a realistic parameter of the optimization of high-frequency amplifiers. These two FOMs, Maximizing RF gain, f_t and f_{max} are the primary goals for RF applications. Small signal AC analysis is performed over a wide frequency range using 2-D device simulator and the vertical direction parameters are calculated. Then, an advanced two port network RF extraction post processing tool is used to generate the different RF-FOMs (f_T and f_{max}) by converting admittance and capacitance to H-parameters.

The E-mode device exhibits slightly enhanced RF characteristics. The peak fT and fmax obtained for E-mode device is 43 GHz and 48 GHz respectively.

V. CONCLUSION

Characterization of the novel Enhancement mode (E-mode) AlInN/GaN HEMT implemented using p-GaN gate is done using 2D Sentaurus TCAD simulation is done using the hydrodynamic model. Hydrodynamic model is used in the simulation. Comprehensive investigation of key FOMs such as Transfer characteristics, *Vt*, transconductance, capacitance and RF gain are done E-mode device. The E-mode device shows lower off-state leakage current, higher I_{on}/I_{off} ratio and lower subthreshold slope (SS). The E-mode device exhibits slightly enhanced RF characteristics as compared to existing devices. These results demonstrate the potential of E-mode AlInN/GaN HEMT device for high speed and high-frequency applications.

VI. ACKNOWLEDGMENT

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