Design of Low Threshold Voltage AlGaN/GaN High Electron Mobility Transistors for High Power Switching and Digital Logic Applications

Bhubesh Chander Joshi
bhubesh25@gmail.com
Optoelectronic Devices Group,
Central Electronics Engineering
Research Institute (CEERI),
CSIR, Pilani-333031 India

Dinesh Kumar
Department of Electronics
Kurukshetra University,
Kurukshetra-136119 India

Raj Kumar Tyagi
Physics Department, H.N.B.
P.G. College Khatima, 262308
India

Chenna Dhanavantri
Optoelectronic Devices Group,
Central Electronics Engineering Research Institute (CEERI),
CSIR, Pilani-333031 India

Abstract

AlGaN/GaN HEMTs has very high threshold voltage, which makes it un-suitable for power devices and digital logic applications. In this study a polarization model for graded channel AlGaN in AlGaN/GaN high electron mobility transistors (HEMTs) has been developed by dividing the graded region into small numbers of elements, of constant Aluminum compositions. The proposed model is further extended to find an expression of total charge density due to non-vanishing polarization charge inside the graded region. A 3 dimensional electron gas (3DEG) is obtained in graded AlGaN/GaN HEMT structures. Predicted threshold voltage for graded HEMTs is lower than in conventional HEMTs. Threshold voltage of the graded device can further be tailored by using different Al composition in graded region. Maximum channel current in graded HEMT device is lower than conventional HEMT. However, with grading in AlGaN, one can grow with higher Al composition in AlGaN layer and can enhance the performance of graded AlGaN/GaN HEMT.

Keywords : Threshold Voltage, GaN, 3-DEG, High-electron mobility transistors (HEMTs), Polarization

1. Introduction

AlGaN/GaN high electron mobility transistors (HEMTs) are promising device for high power and high frequency applications. In comparison to others III-V semiconductor material, GaN material devices can operate at much high temperature, without degradation in performance. Polarization field in GaN materials is much larger than other III-V compound semiconductor materials. Strong polarization field in these materials can accumulate large carriers (n_s~10^{13} cm^{-2}) at AlGaN-GaN hetero interface [1]. Due to non-availability of GaN bulk substrates, GaN devices are normally grown on SiC [2], [3], Si [4]-[6] and sapphire [7]-[10] substrates. SiC is the most suitable material for GaN devices, with the lattice mismatch up to 3 %. The main drawback of SiC substrate is, its high cost. Device performance of GaN HEMTs can further be improved by adjusting growth condition and layer structure. Better performance can be obtained by using high thermal conducting Diamond and SiC substrate materials [11]. Introduction of low temperature nucleation layer [12], annealing [13], Fe [14], delta doping [15]-[17] greatly improved the power, performance and reliability level of AlGaN/GaN HEMT.

Threshold voltage of AlGaN/GaN HEMTs is very large as compared to GaAs HEMT, which makes it improper for high power switching supplies (SMPS) and digital logic circuits. The threshold voltage of AlGaN/GaN HEMT can be tailored by choosing the different doping profile and/or by reducing the thickness of AlGaN layer. AlGaN thickness required for the formation of 2DEG kept a limit on minimum thickness. Gate recessing technique can be used, for achieving low threshold voltage device [18]. But, plasma induced damages [19] and control over few nm etching, kept a limit on quality and size of recess area. Requirements of non leaky Schottky barrier, kept an upper limit on doping density to go beyond 10^{19} cm^{-3} for silicon and 4×10^{20} cm^{-3} for germanium doping [20] for a crack-free n-epitaxial layer. Moreover, structural quality of AlGaN layers typically degrades with increasing Al mole fraction [21].

In this paper, a polarization model for graded (Al composition) AlGaN/GaN HEMT is developed. This model is used in ATLAS simulator for studying the effect of channel grading on threshold voltage of AlGaN/GaN HEMT. At the end of paper a method of enhancing the Al composition in AlGaN/GaN HEMT with grading is detailed studied.

2. Polarization model for Graded AlxGa1-xN HEMT

Total graded region (of thickness = m) is divided into a large number of thin layers, t of thickness dt (= m/t) with constant Al composition. We assumed the Divergence of Displacement Vector (∇.D) is zero inside this thin layer. Piezoelectric polarization for conventional AlGaN layer on GaN is given by [22],

$$P_{pz} = 2\frac{a_s - a_0}{a_0}\left(E_{31} - \frac{E_{33}C_{13}}{C_{33}}\right) \tag{1}$$

where E_{31} and E_{33} are piezoelectric constants, and C_{13} and C_{33} are elastic constants, a_0 and a_s are the lattice constant of un-strained and strained AlGaN layers respectively.

The total polarization in single thin layer is given by sum of spontaneous polarization, P_{spn} and piezoelectric polarization, P_{pzn}

$$P_n = P_{spn} + P_{pzn} \tag{2}$$

where n is variable varies from 1 to t.

The spontaneous and piezoelectric polarization for $Al_xGa_{1-x}N$ layer on GaN as in [22] is given by,

$$P_{spn} = -0.09x_n - 0.034(1-x_n) + 0.021x_n(1-x_n)$$
$$P_{pzn} = -0.0525x_n + 0.0282x_n(1-x_n) \qquad (3)$$

Total polarization in n[th] layer is given by

$$P_n = -0.0492x_n^2 - 0.0593x_n - 0.034 \qquad (4)$$

where x_n is Al composition in n[th] layer and given by,

$$x_n = \frac{(x_{\max} - x_{\min})}{m} n \qquad (5)$$

where m (m= t dt) is total thickness of AlGaN graded layer.

Total polarization of n[th] layer is given by,

$$P_n = -0.0492\frac{(x_{\max} - x_{\min})^2}{m^2} n^2 - 0.0593\frac{(x_{\max} - x_{\min})}{m} n - 0.034 \qquad (6)$$

The total polarization (P_n), spontaneous polarization (P_{spn}) and piezoelectric polarization (P_{pzn}) with respect to different Al composition are shown in Fig. 1.

Net polarization at n[th] interface can be given by

$$P_{tot,n} = P_{n-1} - P_n \qquad (7)$$

$$P_{tot,n} = \frac{0.0492(2n-1)(x_{\max} - x_{\min})^2}{m^2} + 0.0593\frac{(x_{\max} - x_{\min})}{m} \qquad (8)$$

The polarization charge density calculated by this model for t=15 nm and t=30 nm for Al composition varying from 0% to 30% are shown in Fig. 2. Different charge distribution plots are obtained for different values of t, but the total charge per unit distance from gate is same for all cases. And for 30 nm the total charge density of 1.38 x 10^{13}cm^{-2} in obtained in both of above cases.

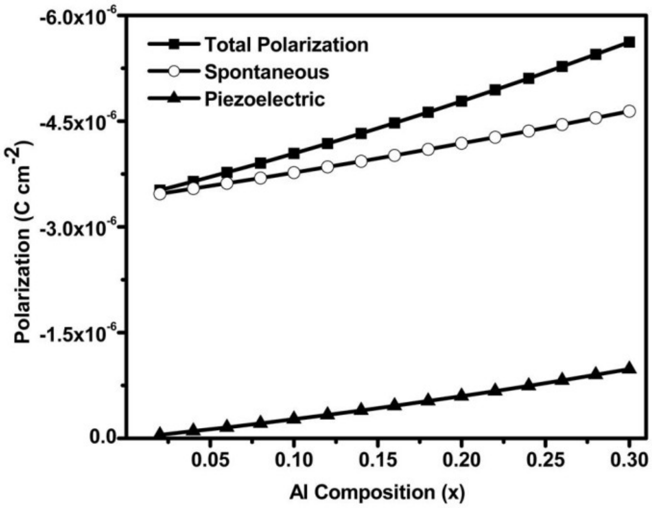

Fig. 1.: Spontaneous, piezoelectric and total polarization for different Al compositions

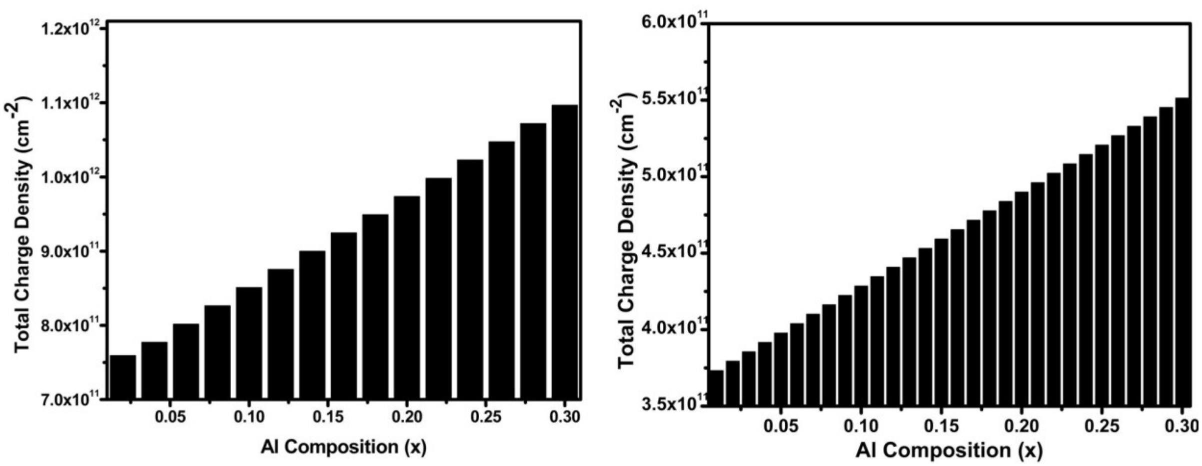

Fig. 2.: Polarization charge density calculated by model for Aluminum composition varying from 0% to 30% , Polarization charge density for (a) t=15 and (b) t=30

3. Simulation of graded AlGaN/GaN HEMT

ATLAS from M/s Silvaco has been used for simulating graded AlGaN/GaN HEMT. Polarization model has been for including the effect of polarization in graded region of AlGaN/GaN HEMT. The schematic of graded AlGaN/GaN HEMT on sapphire used in this study is shown in Fig. 3. The gate length is 1 μm. The source to gate and gate to drain spacing are 2 and 3 μm respectively. Al composition in AlGaN layer is varied, usually from 0 to 30 %. The input device/simulation parameters used in this study are listed in table 1. Conduction band offset between GaN and AlGaN is kept as 0.79. External thermal lumped resistance of 5 x 10^{-3} K/Wcm^2 was used to include the effect of thermal spreading due to the sapphire substrate. To compare graded HEMTs with conventional HEMTs, we also simulate conventional HEMT, MESFET and gate recessed AlGaN/GaN HEMTs with ATLAS.

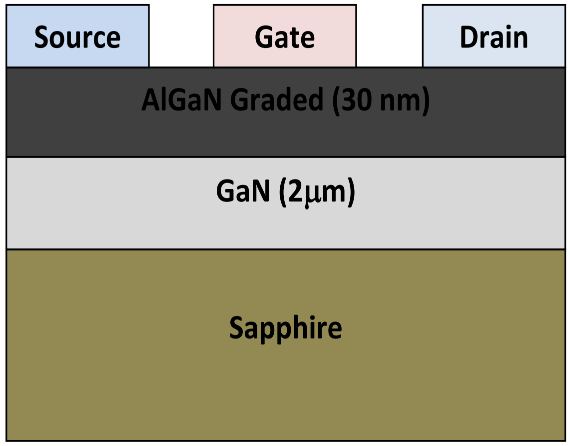

Fig. 3: Schematic of graded AlGaN/GaN High Electron Mobility Transistor

Table I. Device and Materials Parameters Used for Simulation

Parameter	**GaN**	**AlGaN**
Gate metal work function (eV)	-	5.1
Gate metal barrier height (eV)	-	1.3
Electron mobility (cm^2/V-s)	300	250
Hole mobility (cm^2/V-s)	10	*5*
Thermal constant, K (cm-K/W)	0.666	1.47
Heat capacity constant, A (J/K-cm^3)	1.97	1.54
Heat capacity constant, b (J/K^2-cm^3)	0.00036	0
Heat capacity constant, d (J K/cm^3)	$-3.7x10^4$	0

4. Results and Discussion

I-V and transfer characteristics obtained for conventional and graded AlGaN/GaN HEMT devices are compiled in table 2. The transfer curve, I_{ds}-V_{gs} for graded and conventional HEMT devices are shown in Fig. 4. The threshold voltage for graded HEMT with Al composition from 0 to 30 % is -3.5 V and for conventional HEMT it is -8 V. By varying the composition from 0 to

30 then again to 0 %, threshold voltage of graded HEMT decreases to -3 V. The threshold voltage of graded HEMT device can be further tailored down by varying the Al composition.

Table II Result Extracted from Different Devices

Sr. No.	**Device**	**Al composition (x)**	**I_{ds} max (mA/mm)**	**g_m (mS/mm)**	**Threshold Voltage (V)**
1	Conventional	30	650	150	-8
2	Graded	0 to 30	425	136	-3.5
3	Graded	0 to 20	247	128	-2
4	Graded	10 to 30	206	100	-2.5
5	Graded	0-30-0	248	102	-3
6	Graded	0-30-10	251	88	-4
7	Graded	0-30-15	334	120	-4
8	Graded	0-30-20	378	126	-4.5
9	Graded	0-30-25	414	130	-5
10	Graded	0-30-30	420	132	-5.5
11	Graded	0 to 45	620	145	-5.5

Maximum transconductance, g_m of 136 mS/mm is obtained for graded HEMT with Al composition varying from 0 to 30%. Maximum channel current, I_{ds} of 425mA/mm is obtained in this device. Maximum transconductance of 150 mS/mm and maximum channel current of 650 mA/mm is obtained for conventional HEMT. The fall in the maximum channel current in the graded device may be due to the formation of channel in AlGaN, where the carrier concentration is high and carrier transport in this region is largely influenced by ionization impurity scattering at room temperature. Device heating occurs in both devices, which degrade the performance of the device and thus cause a negative differential conductance region in, I-V curves as shown in Fig. 5. The conduction band edges of conventional and graded HEMT are shown in Fig. 6 and Fig. 7 respectively. A 3 Dimension electron gas (3DEG) with region thickness of 15 nm in AlGaN, is obtained in the band diagram of graded HEMT. This thickness is abnormal compared to the region thickness of the order of 2 – 3 nm in 2DEG conventional HEMTs.

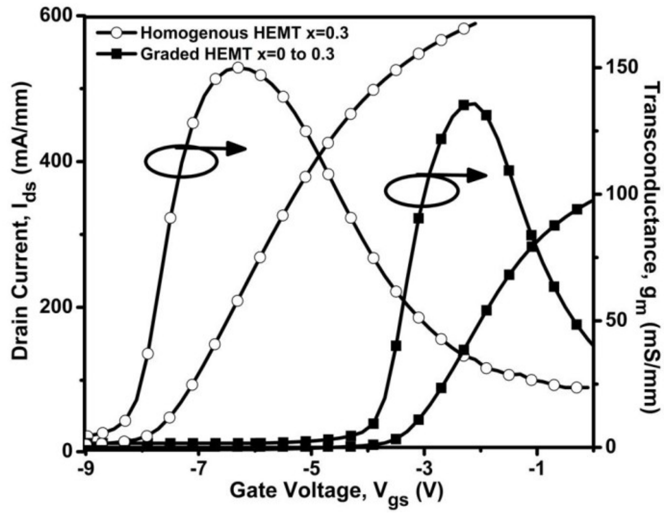

Fig. 4: Transfer curves for Conventional (x=0.3) and Graded AlGaN/GaN HEMT (x_{min}=0 and x_{max}=0.3).

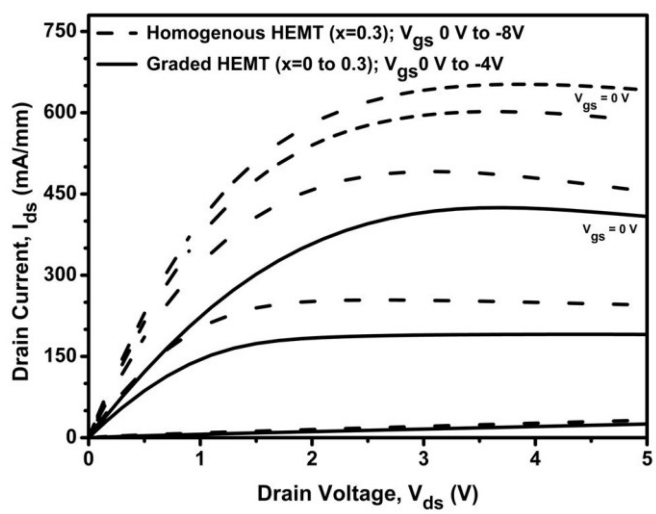

Fig. 5: I-V Characteristics for Conventional (x=0.3) and Graded AlGaN/GaN HEMT (x_{min}=0 and x_{max}=0.3).

Conduction band diagram for doped AlGaN/GaN MESFET with x=0.3 nm and 100 nm AlGaN layer is shown in Fig. 8. A 3 dimension electron gas is observed when doping exceeded 10^{18} cm^{-3}. Graded HEMT band diagram looks equivalent to doped channel MESFET band diagram. The graded device shows high mobility and better performance than MESFET due to low ionized scattering.

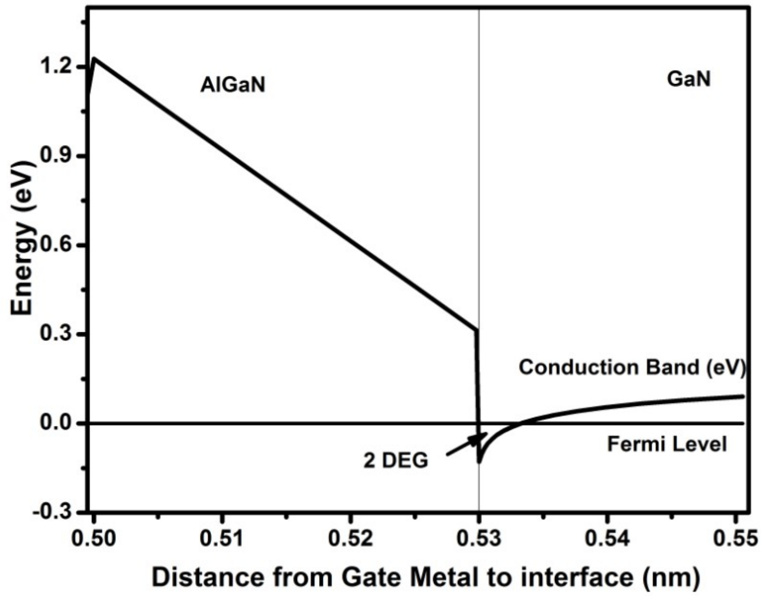

Fig. 6: Conduction band edge of Conventional AlGaN/GaN HEMT

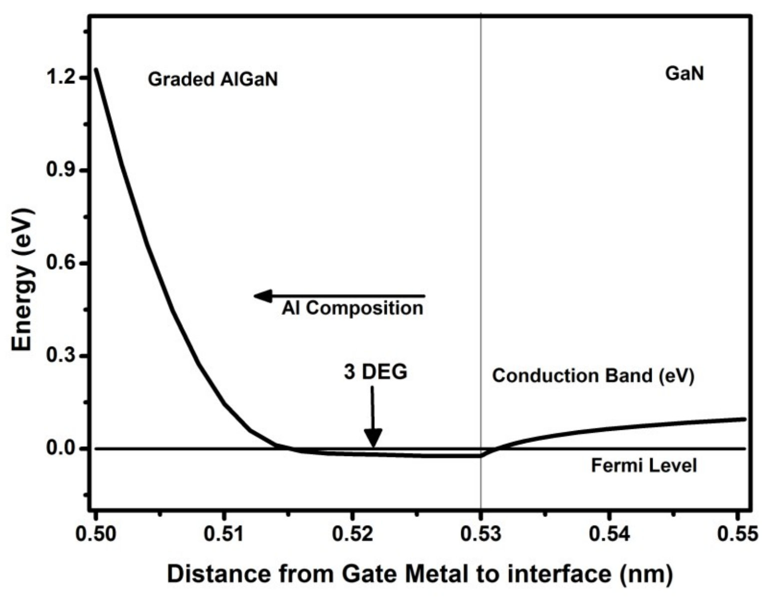

Fig. 7: Conduction band diagram of the graded device with Al composition varying from 0 to 30%

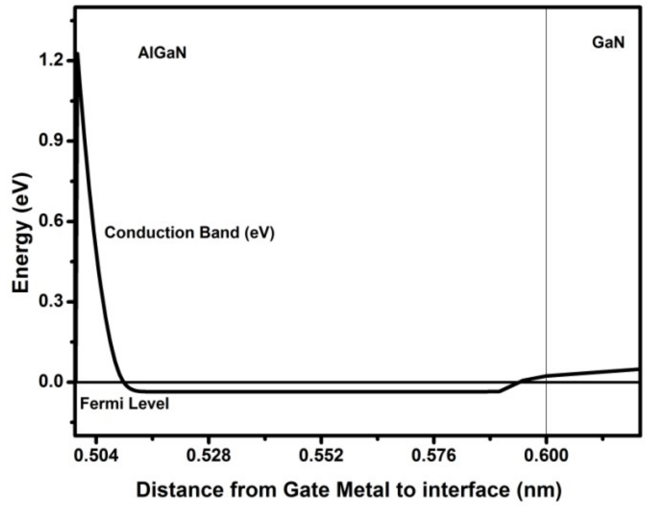

Fig. 8: Conduction band edge of MESFET for $n_d = 10^{19}$

Maximum Al composition, up to which a high quality strained AlGaN epitaxial layer can be grown on GaN buffer, is 30 to 35%. The increase in the dislocation density, beyond this mole fraction is related to the lower surface mobility of Al species in comparison to Ga species. This is due to the higher bond strength between Al and nitrogen, in AlGaN (2.88 eV), in comparison to GaN (2.2 eV). Furthermore, for Al composition beyond 35 %, the lattice mismatch between GaN and AlGaN is so high that it results in stress, and further degrades the performance of the device. However, with the graded layers we can grow higher Al composition material with low dislocation density and stresses. With higher Al composition, total polarization charge in 3DEG increases, which results in the increase in the drain current.

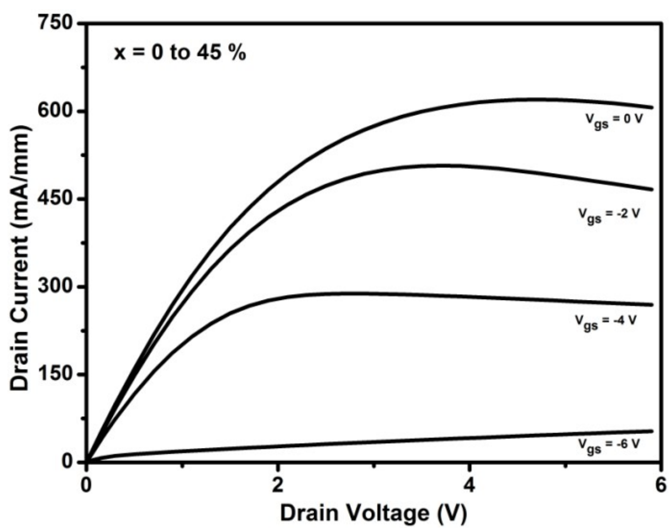

Fig. 9: I-V characteristics of Graded device with higher Al composition

The I-V characteristics of graded AlGaN/GaN HEMT device with Al composition variation from 0 to 45 % is shown in Fig. 9. The maximum drain current of 620mA/mm and the maximum transconductance of 145 mS/mm are obtained in this case.

Threshold voltage of graded structure can be further reduced by gate recessing. The simulation has been done for graded AlGaN/GaN HEMT structure with gate recessing. The threshold voltage of recess structure depends upon the recessing depth and a enhance performance (Threshold voltage of +0.5V) is obtained at gate recess of 25 nm in graded structure with Al composition varying from 0 to 65%. This structure shows maximum channel current of 175 mA/mm at V_{gs} = 1V.

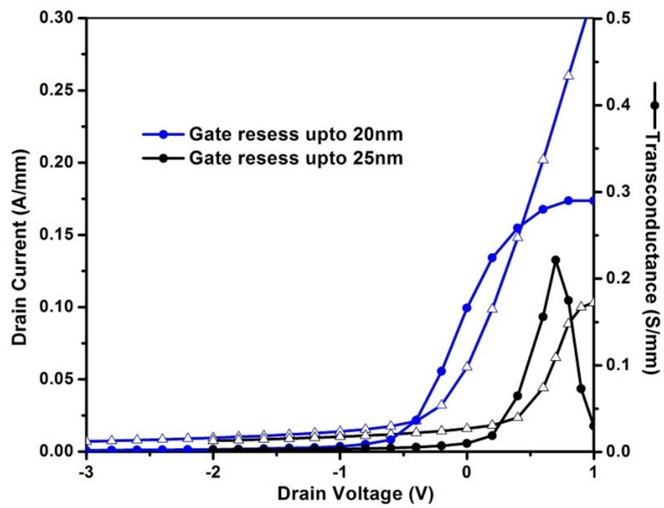

Fig. 10: Effect of gate recessing in Graded AlGaN/GaN HEMTs

5. Conclusions

We have developed a polarization model for graded AlGaN layer. This model is used to extract characteristics of graded AlGaN/GaN HEMT. Output characteristics of graded AlGaN channel HEMT is compared with conventional HEMT and MESFET. Threshold voltage of the graded device is found to be lower than that of conventional HEMT device. The threshold voltage of the graded device can be further tailored by varying the Al composition and by using different grading profiles. One may obtain reduced threshold voltage up to + 0.5 V by gate recessing up to 25 nm, which make enhancement-mode AlGaN/GaN HEMT which suitable for SMPS and digital logic circuit. A 3DEG with abnormal region thickness of 15 nm is obtained in graded AlGaN/GaN HEMT device. The higher Al composition > 45 % can be grown with graded AlGaN/GaN HEMT device and the performance of graded channel device can be further increased with low threshold voltage.

ACKNOWLEDGMENT

The authors would like to thanks the Director, Central Electronics Engineering Research Institute (CEERI), Pilani, for his encouragement, and members of the Optoelectronic Devices Group and Semiconductor Device Fabrication Facility, CEERI, for their help at various stages. One of the authors acknowledges CSIR, for financial support.

References

[1] J.P. Ibbeton, P.T. Fini, K.D. Ness, S.P. DenBaars, J.S. Speck, and U.K. Mishra, "Polarization Effects, Surface States, and the Source of Electrons In Algan/Gan Heterostructure Field Effect Transistors", Appl. Phys. Lett. vol. 77, 2000, pp. 250-252.

[2] S. Rajan, P. Waltereit, C. Poblenz, S. J. Heikman, D. S. Green, J. S. Speck, and U. K. Mishra, "Power Performance of AlGaN–GaN HEMTs Grown on SiC by Plasma-Assisted MBE", IEEE Electron Device Letter, vol. 25, 2004, pp. 247-249.

[3] J. W. Johnson, J. Han, A. G. Baca, R. D. Briggs, R. J. Shul, J. R. Wendt, C. Monier, F. Ren, B. Luo, S. N. G. Chu, D. Tsvetkov, V. Dmitriev, and S. J. Pearton, "Comparison of AlGaN/GaN High Electron Mobility Transistors Grown on AlN/SiC Templates or Sapphire", Solid State Electronics, vol. 46, 2002, pp. 513-523.

[4] S. Pal, and C. Jacob, "Silicon-A New Substrate for GaN growth", Bull. Mater. Sci., vol. 27, 2004, pp. 501-504

[5] S. Iwakami, O. Machida, M. Yanagihara, T. Ehara, N.Kaneko, H. Goto, and A. Iwabuchi, "20mΩ, 750V High-Power AlGaN/GaN Heterostructure Field-Effect Transistors on Si Substrate", Japanese Journal of Applied Physics, vol. 46, 2007, pp. L587- L589.

[6] C.-T. Liang, Kuang Yao Chen, N. C. Chen, P. H. Chang, and Chin-An Chang, "$Al_{0.15}Ga_{0.85}N$/GaN High Electron Mobility Transistor Structures Grown on *p*-type Si Substrates", Applied Physics Letter, vol. 89, 2006, pp. 132107_1-3.

[7] D. S. Wuu, W. K. Wang, K. S. Wen, S. C. Huang, S. H. Lin, S. Y. Huang, C. F. Lin, and R. H. Horng, "Defect Reduction and Efficiency Improvement of Near-Ultraviolet Emitters via Laterally Overgrown GaN on a GaN/patterned Sapphire Template", Appl. Phys. Lett. vol. 89, 2006, pp. 161105_1-3.

[8] X. Q. Shen, H. Okumura, K. Furuta, and N. Nakamura, "Electrical Properties of AlGaN/GaN Heterostructures Grown on Vicinal Sapphire (0001) Substrates by Molecular Beam Epitaxy", Appl. Phys. Lett., vol. 89, 2006, pp. 171906_1-3.

[9] S. Raghavan, and J. M. Redwing, "Intrinsic stresses in AlN Layers Grown by Metal Organic Chemical Vapor Deposition on (0001) Sapphire and (111) Si Substrates", J. Appl. Phys., vol. 96, 2004, pp. 2995-3003

[10] V. Soukhoveev, O. Kovalenkov, l. Shapovalova, V. Ivantsov, A. Usikov, V. Dmitrie, V. Davydov, and A. Smirnov, "AlGaN Epitaxial Layers Grown by HVPE on Sapphire Substrates", Phys. Stat. Sol. (c), vol. 3, 2006, pp. 1483-1486.

[11] B. C. Joshi, C. Dhanavantri, and D. Kumar, "Sapphire, SiC, AlN, Si and Diamond-substrate Material for GaN HEMT and LED", Journal Of Optoelectronics And Advanced Materials, vol. 11, 2009, pp. 1111-1116

[12] Akasaki, H. Amano, Y. Koide, K. Hiramatsu, and N. Sawaki, "Effects of ain buffer layer on crystallographic structure and on electrical and optical properties of GaN and $Ga_{1-x}Al_xN$ ($0 < x < 0.4$) Films Grown on Sapphire Substrate by MOVPE", Journal of Crystal Growth, vol. 98, 1989, pp. 209-219

[13] C. F. Lin, G. C. Chi, M. S. Feng, J. D. Guo, J. S. Tsang, and J. Minghuang Hong, "The dependence of the electrical characteristics of the GaN Epitaxial Layer on the Thermal Treatment of the GaN Buffer Layer", Appl. Phys. Lett., vol. 68, 1996, 3758-3760

[14] Chul Choi Young, Cha Ho-Young, G. Spencer Michael and F. Eastman Lester, "The Effect of an Fe-doped GaN Buffer on off-State Breakdown Characteristics in AlGaN/GaN HEMTs on Si Substrate", IEEE Transactions on Electron Devices, vol. 53, 2006, pp. 2926-2931

[15] B.C. Joshi, N. Pradhan, M. Mathew, K. Singh, C. Dhanavantri and D. Kumar, “Delta doping: New Technique to Reduce Current Crowding Problem in III-nitride LEDs”, Optoelectronics and Advanced Materials-Rapid Communications, vol. 3, pp. 985-988

[16] Y.B. Pan, Z.J. Yang, Z.T. Chen, Y. Lu, T.J. Yu, X.D. Hu, K. Xu, and G.Y. Zhang, “Reduction of Threading Edge Dislocation Density in n-type GaN by Si Delta-Doping”, Journal of Crystal Growth, vol. 286, 2006, pp. 255–258

[17] H. Lahre Che, P. Venne Gue, B. Beaumont, and P. Gibart, “Growth of high-quality GaN by Low-Pressure Metal-Organic Vapour Phase Epitaxy (LP-MOVPE) from 3D Islands and Lateral Overgrowth”, Journal of Crystal Growth, vol. 205, 1999, pp. 245-252

[18] W.B. Lanford, T. Tanaka, Y. Otoki and I. Adesida, “Recessed-Gate Enhancement-Mode GaN HEMT with High Threshold Voltage”, Electronic Letters, vol. 41, 2005, pp. 449-450

[19] Xian an Cao, “Advance Processing of GaN for Novel Electronic Device”, Thesis: University of Florida, Florida, 2000

[20] P.R. Hageman, W.J. Schaff, Jacek Janinski, and Zuzanna Liliental-Weber, “n-Type Doping of Wurtzite GaN with Germanium Grown with Plasma-Assisted Molecular Beam Epitaxy”, Journal of Crystal Growth, vol. 267, 2004, pp. 123-128

[21] Y. Koide, H. Itoh, M.R.H. Khan, K. Hiramatu, N.Sawaki, and I. Akasaki, “Energy Band-gap Bowing Parameter in an Al_xGa_{1-x} N Alloy”, J. Appl. Phys., vol. 61, 1987, pp. 4540-4543

[22] O. Ambacher and V. Cimalla, “Polarization Induced Effects in GaN-based Heterostructures and Novel Sensors”, in: Colin Wood, Debdeep Jena (Eds), “Polarization Effects in Semiconductors”, Springer, New York , 2007, pp. 27-110.