Effects of Drain Voltage, Gate Voltage and Aluminium Mole Fraction on Drain Current in GaN based Single-Heterojunction HEMTs designed with AlGaN Nano-Layers

Avrajyoti Dutta[1], Sanjib Kalita[2], Subhadeep Mukhopadhyay[1,*]
[1]Department of Electronics and Communication Engineering, National Institute of Technology Arunachal Pradesh, India
[2]Department of Electronics and Communication Engineering, Rajeev Gandhi Memorial College of Engineering and Technology, Nandyal, Kurnool, Andhra Pradesh, India

Abstract
In this work, we have studied the effect of drain voltage on drain current in single-heterojunction AlGaN/GaN high electron mobility transistors (HEMTs). Also, we have studied the effect of gate voltage on drain current in same set of HEMTs. The effect of aluminium mole fraction on drain current is also studied in the HEMTs designed with AlGaN nano-layers. This work may be helpful to realize the characteristics of HEMT based sensors in future.

Keywords: *Drain voltage, gate voltage, mole fraction, nano-layer, drain current*

***Author for Correspondence** E-mail: subhadeepmukhopadhyay21@gmail.com

INTRODUCTION

Recently, Brown has mentioned the brief history of gallium nitride (GaN) based technology related to the commercial market of power electronics. GaN is proved to be an efficient material due to its energy band gap. Also, the experimental process steps for GaN are briefly mentioned. GaN is highly suitable to fabricate the high electron mobility transistors. Brown has performed the experimental modeling of AlGaN/GaN enhancement mode HEMTs [1].

Few authors have proposed the theoretical model of AlGaN/GaN HEMTs using Robin boundary condition. They have theoretically demonstrated the variations in 2DEG sheet concentration with respect to gate voltage [2]. In a couple of earlier reports, the effects of electrical parameters and structural parameters on drain current have been studied in GaN based HEMTs [3, 4]. Few authors have theoretically presented the analytical models on GaN based HEMTs by brief comparisons with experimental models [5–8]. Few other authors have reported many physics based analytical models on GaN based HEMTs towards the applications in power electronics industry [9–19]. HEMTs may be useful in sensor technology also [20, 21].

In this work, we have studied the effect of drain voltage on drain current in AlGaN/GaN HEMTs. Also, we have studied the effect of gate voltage on drain current in the same set of HEMTs. Next, we have studied the effect of aluminium mole fraction on drain current in the same set of HEMTs designed with AlGaN nano-layers. These studies have been performed using the SILVACO-ATLAS software tool. Our studies may be useful to fabricate the GaN based HEMTs experimentally in future.

DESIGNS OF SIMULATED STRUCTURES

In this work, a representative cross-sectional view of the microelectronic single-heterojunction AlGaN/GaN HEMT structures is shown in Figure 1. The cross-sectional dimensions of different portions of these designed HEMT-structures are given below: (A) Source dimensions are 500 nm (length)×100 nm (height); (B) Drain dimensions are 500 nm (length)×100 nm (height); (C) Gate dimensions are L_G (length)×500 nm (height); (D) Total horizontal length of the device is 9500 nm; (E) GaN thickness is 500 nm; (F) Sapphire thickness is 1000 nm; and (G) Source to gate fixed distance is 3000 nm. In this work, the gate

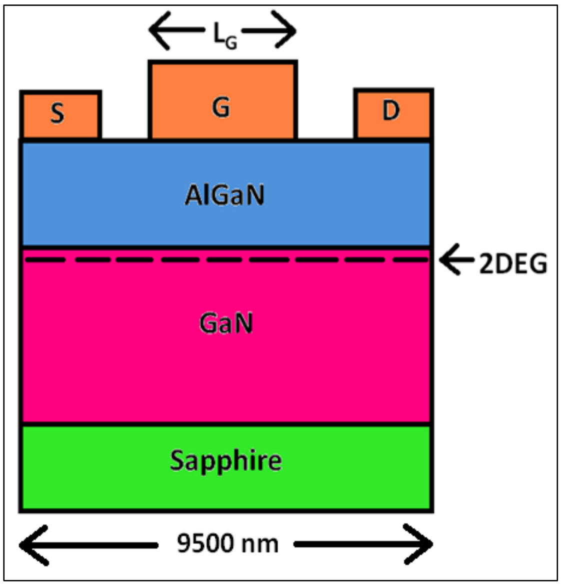

***Fig. 1:** Representative schematic diagram of the single-heterojunction AlGaN/GaN HEMT structures is shown.*

length (L_G) is varied with the following lengths as 1.4, 1.9, 2.4, 2.9, and 3.4 micron. With the variation in gate length, the source to gate distance is fixed (3000 nm), but the gate to drain distance is variable. The selected thicknesses of AlGaN nano-layersare29 nm, 31 nm, 32 nm, 33 nm, and 34 nm. The selected aluminium mole fractions (x) are 0.10, 0.15, 0.20, 0.25, and 0.30. In this work, total 25 individual HEMT-structures are designed and simulated according to the selected combinations of structural parameters. GaN and sapphire are chosen as the materials to design the HEMT structures according to the already reported comparative material properties with respect to other materials [1, 2]. In this work, the AlGaN doping concentration is maintained as 1×10^{18} cm^{-3} in each HEMT structure.

RESULTS AND DISCUSSION

In the first group of HEMTs, the AlGaN thickness (T) is 29 nm and gate length (L_G) is 1.4 micron. According to Figure 2, drain current increases with drain voltage corresponding to the AlGaN thickness (T) of 29 nm, gate length (L_G) of 1.4 micron and gate voltage (V_G) of 0 volt [3, 4]. In Figure 2, the drain current increases due to higher aluminium mole fraction (x). According to Figure 3, drain current increases with drain voltage corresponding to the AlGaN thickness (T) of 29 nm, gate length (L_G) of 1.4 micron and gate voltage (V_G) of -1 volt [3, 4]. In Figure 3, the drain current increases due to higher aluminium mole fraction (x). According to Figure 4, drain current increases with drain voltage corresponding to the AlGaN thickness (T) of 29 nm, gate length (L_G) of 1.4 micron and gate voltage (V_G) of -2 volt [3, 4].

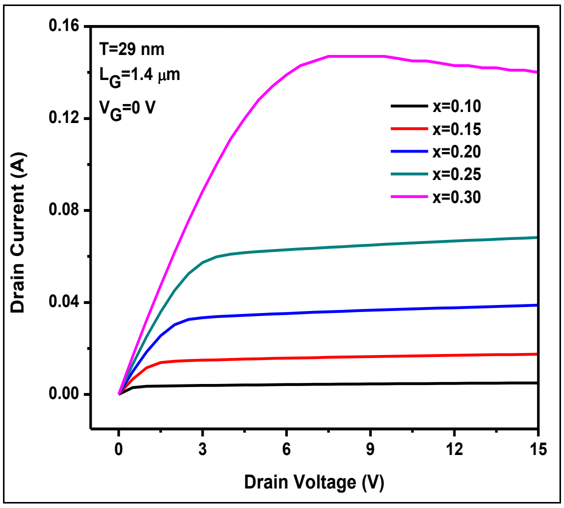

***Fig. 2:** The variation of drain current with respect to drain voltage is shown corresponding to the gate voltage (V_G) of 0 volt, gate length (L_G) of 1.4 micron and AlGaN thickness (T) of 29 nm. The variation of drain current is also shown with respect to aluminium mole fraction (x).*

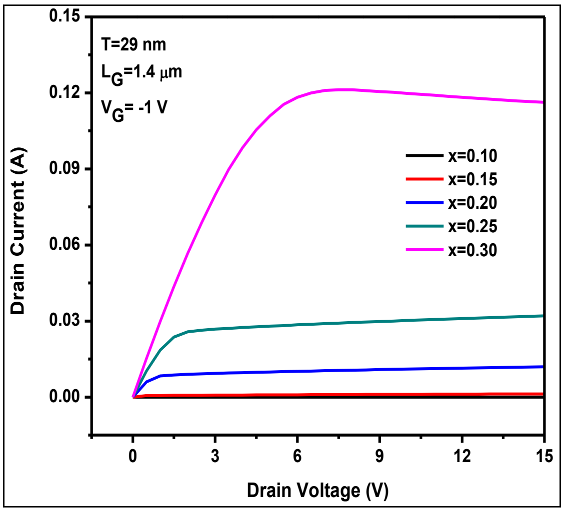

***Fig. 3:** The variation of drain current with respect to drain voltage is shown corresponding to the gate voltage (V_G) of -1 volt, gate length (L_G) of 1.4 micron and AlGaN thickness (T) of 29 nm. The variation of drain current is also shown with respect to aluminium mole fraction (x).*

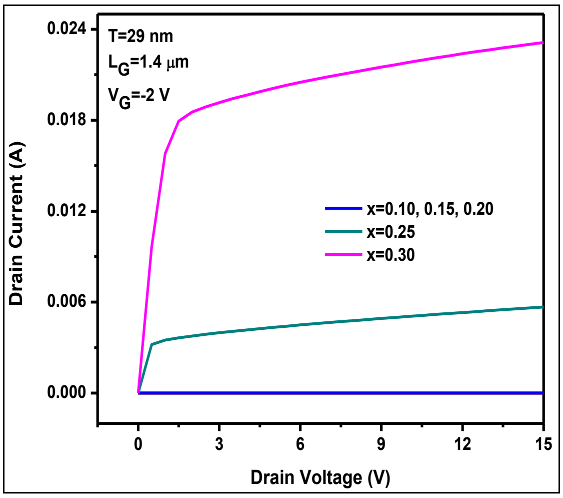

Fig. 4: *The variation of drain current with respect to drain voltage is shown corresponding to the gate voltage (V_G) of -2 volt, gate length (L_G) of 1.4 micron and AlGaN thickness (T) of 29 nm. The variation of drain current is also shown with respect to aluminium mole fraction (x).*

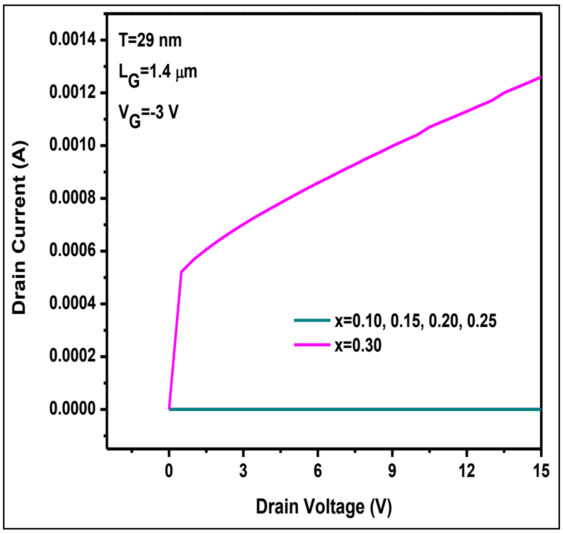

Fig. 5: *The variation of drain current with respect to drain voltage is shown corresponding to the gate voltage (V_G) of -3 volt, gate length (L_G) of 1.4 micron and AlGaN thickness (T) of 29 nm. The variation of drain current is also shown with respect to aluminium mole fraction (x).*

In Figure 4, the drain current increases due to higher aluminium mole fraction (x). According to Figure 5, drain current increases with drain voltage corresponding to the AlGaN thickness (T) of 29 nm, gate length (L_G) of 1.4 micron and gate voltage (V_G) of -3 volt [3, 4].

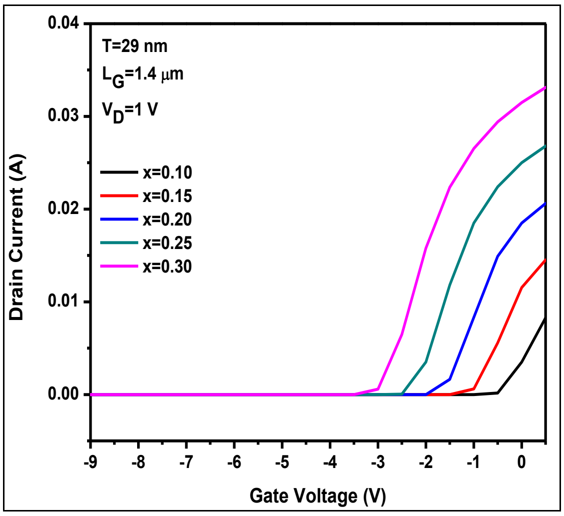

Fig. 6: *The variation of drain current with respect to gate voltage is shown corresponding to the drain voltage (V_D) of 1 volt, gate length (L_G) of 1.4 micron and AlGaN thickness (T) of 29 nm. The variation of drain current is also shown with respect to aluminium mole fraction (x).*

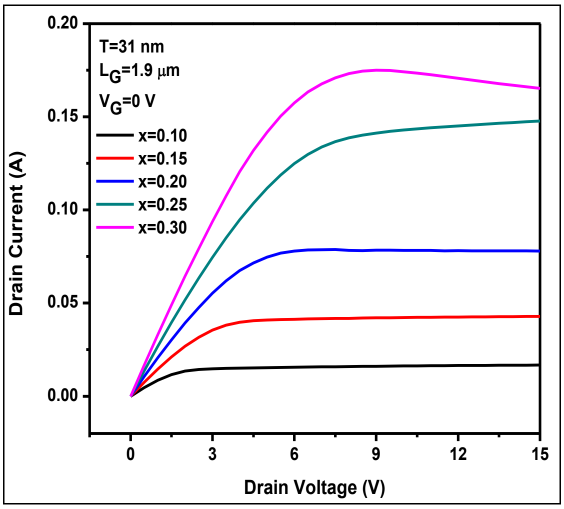

Fig. 7: *The variation of drain current with respect to drain voltage is shown corresponding to the gate voltage (V_G) of 0 volt, gate length (L_G) of 1.9 micron and AlGaN thickness (T) of 31 nm. The variation of drain current is also shown with respect to aluminium mole fraction (x).*

In Figure 5, the drain current increases due to higher aluminium mole fraction (x). In Figure 6, drain current is higher at higher gate voltage corresponding to the AlGaN thickness (T) of 29 nm, gate length (L_G) of 1.4 micron and fixed drain voltage (V_D) of 1 volt [3, 4]. Also, in Figure 6, the drain current is higher due to larger aluminium mole fraction (x).

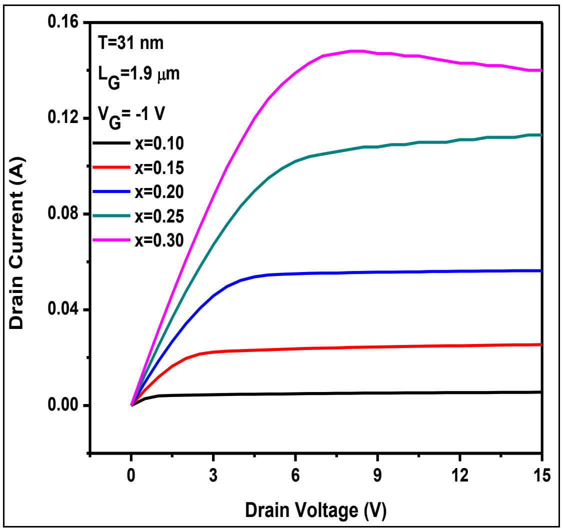

Fig. 8: *The variation of drain current with respect to drain voltage is shown corresponding to the gate voltage (V_G) of -1 volt, gate length (L_G) of 1.9 micron and AlGaN thickness (T) of 31 nm. The variation of drain current is also shown with respect to aluminium mole fraction (x).*

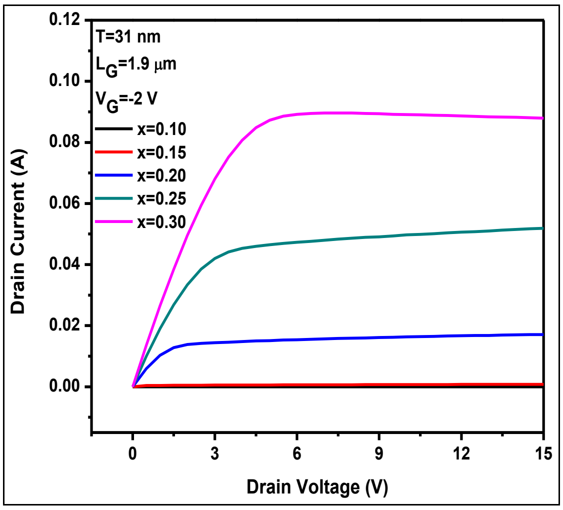

Fig. 9: *The variation of drain current with respect to drain voltage is shown corresponding to the gate voltage (V_G) of -2 volt, gate length (L_G) of 1.9 micron and AlGaN thickness (T) of 31 nm. The variation of drain current is also shown with respect to aluminium mole fraction (x).*

In the second group of HEMTs, the AlGaN thickness (T) is 31 nm and the gate length (L_G) is 1.9 micron. In Figures 7 to 11, the variations in drain current are shown with respect to drain voltage, gate voltage and aluminium mole fraction corresponding to the AlGaN thickness (T) of 31 nm with gate length (L_G) of 1.9 micron. Drain current variations with respect to drain voltage, gate voltage and aluminium mole fraction in second group of designs show similar trends as that of first group of designs [3, 4].

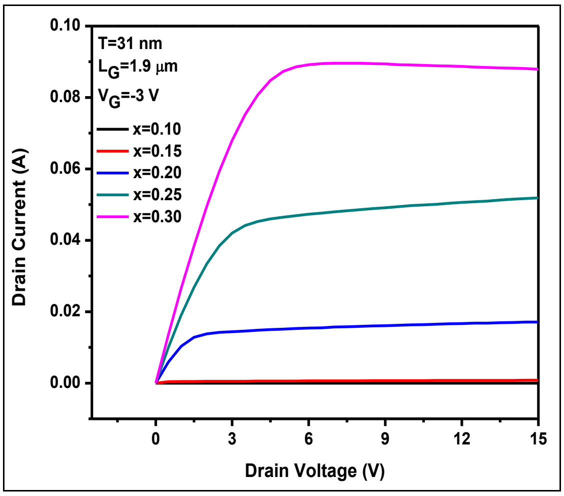

Fig. 10: *The variation of drain current with respect to drain voltage is shown corresponding to the gate voltage (V_G) of -3 volt, gate length (L_G) of 1.9 micron and AlGaN thickness (T) of 31 nm. The variation of drain current is also shown with respect to aluminium mole fraction (x).*

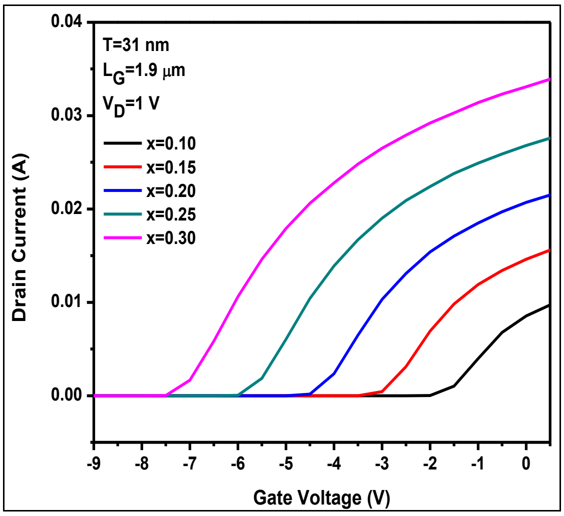

Fig. 11: *The variation of drain current with respect to gate voltage is shown corresponding to the drain voltage (V_D) of 1 volt, gate length (L_G) of 1.9 micron and AlGaN thickness (T) of 31 nm. The variation of drain current is also shown with respect to aluminium mole fraction (x).*

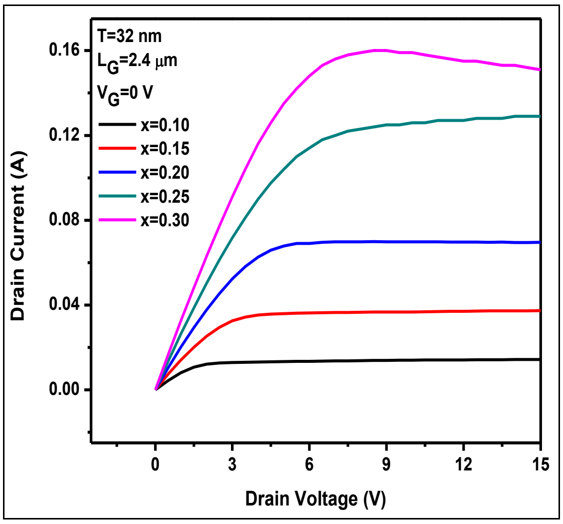

Fig. 12: *The variation of drain current with respect to drain voltage is shown corresponding to the gate voltage (V_G) of 0 volt, gate length (L_G) of 2.4 micron and AlGaN thickness (T) of 32 nm. The variation of drain current is also shown with respect to aluminium mole fraction (x).*

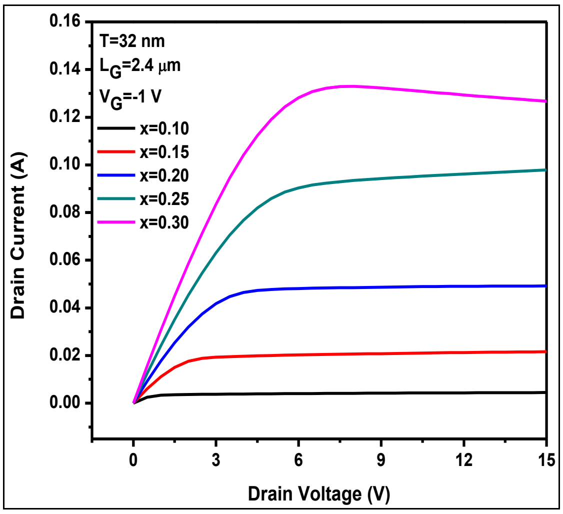

Fig. 13: *The variation of drain current with respect to drain voltage is shown corresponding to the gate voltage (V_G) of -1 volt, gate length (L_G) of 2.4 micron and AlGaN thickness (T) of 32 nm. The variation of drain current is also shown with respect to aluminium mole fraction (x).*

In the third group of HEMTs, the AlGaN thickness (T) is 32 nm and the gate length (L_G) is 2.4 micron. In Figures 12 to 16, the variations in drain current are shown with respect to drain voltage, gate voltage and aluminium mole fraction corresponding to the AlGaN thickness (T) of 32 nm with gate length (L_G) of 2.4 micron. Drain current variations with respect to drain voltage, gate voltage and aluminium mole fraction in third group of designs show similar trends as that of first group of designs [3, 4].

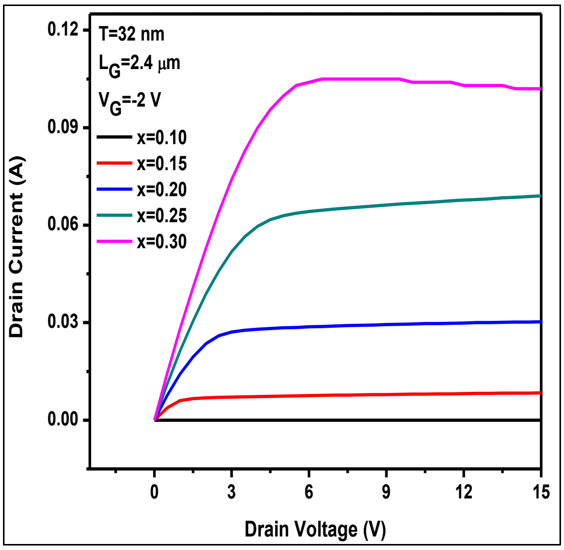

Fig. 14: *The variation of drain current with respect to drain voltage is shown corresponding to the gate voltage (V_G) of -2 volt, gate length (L_G) of 2.4 micron and AlGaN thickness (T) of 32 nm. The variation of drain current is also shown with respect to aluminium mole fraction (x).*

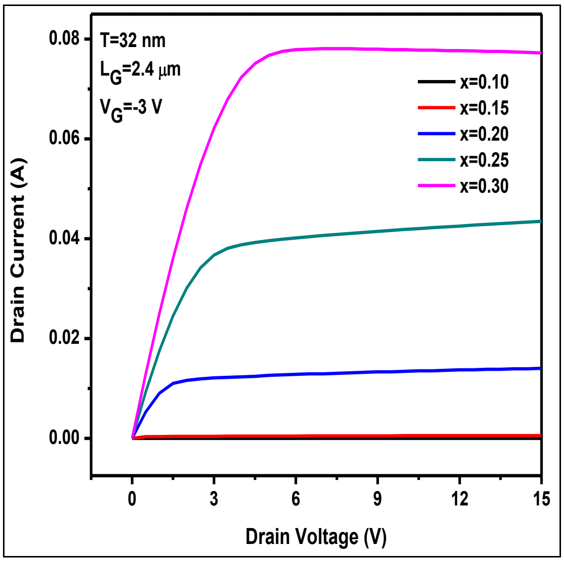

Fig. 15: *The variation of drain current with respect to drain voltage is shown corresponding to the gate voltage (V_G) of -3 volt, gate length (L_G) of 2.4 micron and AlGaN thickness (T) of 32 nm. The variation of drain current is also shown with respect to aluminium mole fraction (x).*

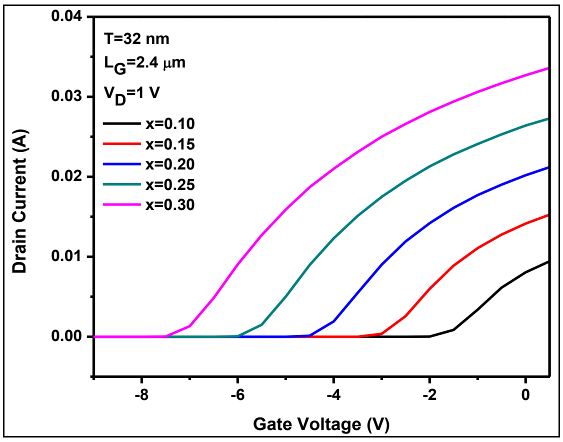

Fig. 16: *The variation of drain current with respect to gate voltage is shown corresponding to the drain voltage (V_D) of 1 volt, gate length (L_G) of 2.4 micron and AlGaN thickness (T) of 32 nm. The variation of drain current is also shown with respect to aluminium mole fraction (x).*

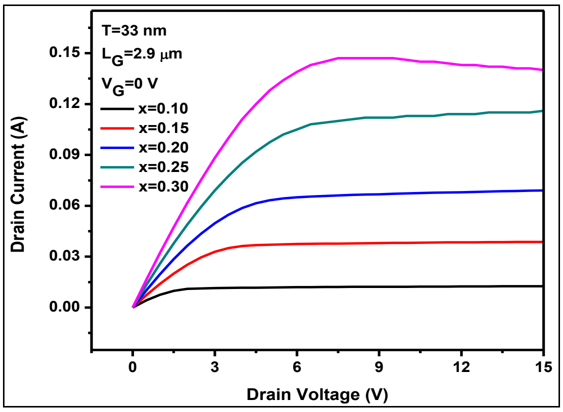

Fig. 17: *The variation of drain current with respect to drain voltage is shown corresponding to the gate voltage (V_G) of 0 volt, gate length (L_G) of 2.9 micron and AlGaN thickness (T) of 33 nm. The variation of drain current is also shown with respect to aluminium mole fraction (x).*

In the fourth group of HEMTs, the AlGaN thickness (T) is 33 nm and the gate length (L_G) is 2.9 micron. In Figures 17 to 21, the variations in drain current are shown with respect to drain voltage, gate voltage and aluminium mole fraction corresponding to the AlGaN thickness (T) of 33 nm with gate length (L_G) of 2.9 micron. Drain current variations with respect to drain voltage, gate voltage and aluminium mole fraction in fourth group of designs show similar trends as that of first group of designs [3, 4].

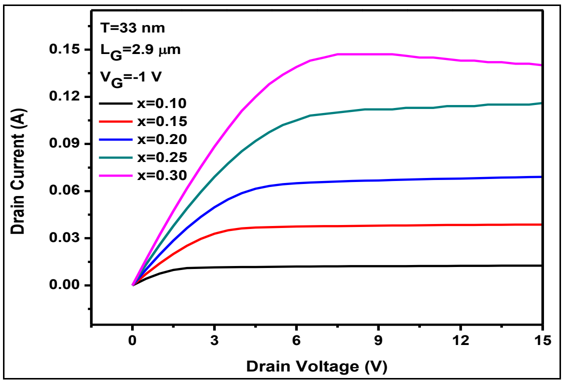

Fig. 18: *The variation of drain current with respect to drain voltage is shown corresponding to the gate voltage (V_G) of -1 volt, gate length (L_G) of 2.9 micron and AlGaN thickness (T) of 33 nm. The variation of drain current is also shown with respect to aluminium mole fraction (x).*

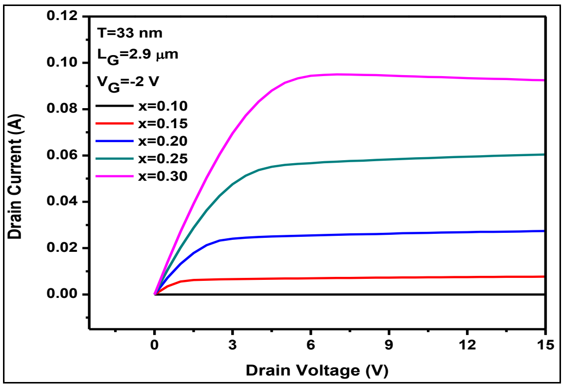

Fig. 19: *The variation of drain current with respect to drain voltage is shown corresponding to the gate voltage (V_G) of -2 volt, gate length (L_G) of 2.9 micron and AlGaN thickness (T) of 33 nm. The variation of drain current is also shown with respect to aluminium mole fraction (x).*

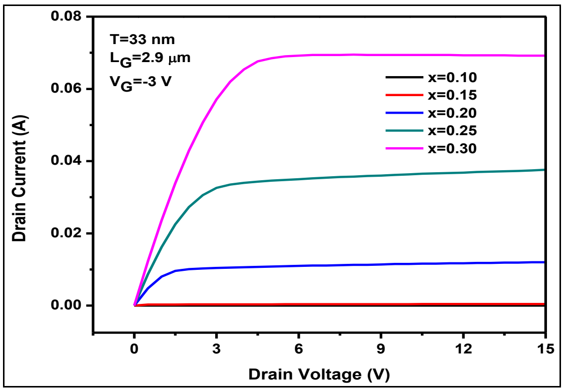

Fig. 20: *The variation of drain current with respect to drain voltage is shown corresponding to the gate voltage (V_G) of -3 volt, gate length (L_G) of 2.9 micron and AlGaN thickness (T) of 33 nm. The variation of drain current is also shown with respect to aluminium mole fraction (x).*

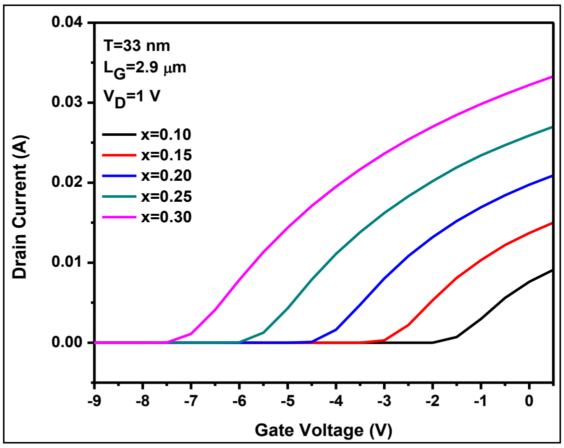

Fig. 21: *The variation of drain current with respect to gate voltage is shown corresponding to the drain voltage (V_D) of 1 volt, gate length (L_G) of 2.9 micron and AlGaN thickness (T) of 33 nm. The variation of drain current is also shown with respect to aluminium mole fraction (x).*

In the fifth group of HEMTs, the AlGaN thickness (T) is 34 nm and the gate length (L_G) is 3.4 micron. In Figures 22 to 26, the variations in drain current are shown with respect to drain voltage, gate voltage and aluminium mole fraction corresponding to the AlGaN thickness (T) of 34 nm with gate length (L_G) of 3.4 micron. Drain current variations with respect to drain voltage, gate voltage and aluminium mole fraction in fifth group of designs show similar trends as that of first group of designs [3, 4].

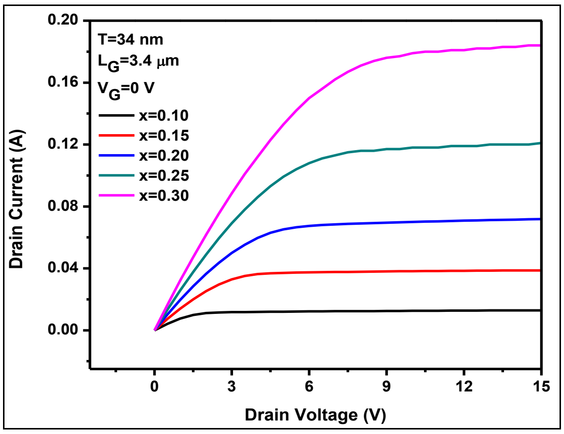

Fig. 22: *The variation of drain current with respect to drain voltage is shown corresponding to the gate voltage (V_G) of 0 volt, gate length (L_G) of 3.4 micron and AlGaN thickness (T) of 34 nm. The variation of drain current is also shown with respect to aluminium mole fraction (x).*

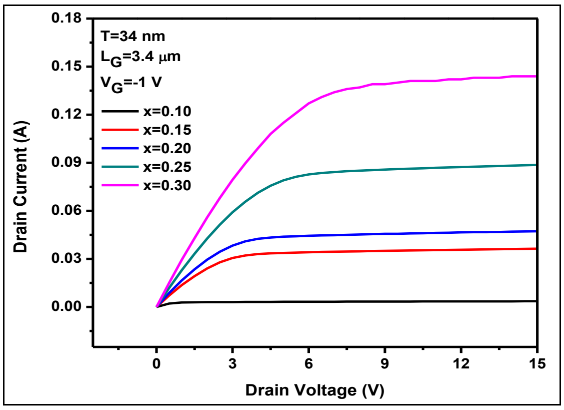

Fig. 23: *The variation of drain current with respect to drain voltage is shown corresponding to the gate voltage (V_G) of -1 volt, gate length (L_G) of 3.4 micron and AlGaN thickness (T) of 34 nm. The variation of drain current is also shown with respect to aluminium mole fraction (x).*

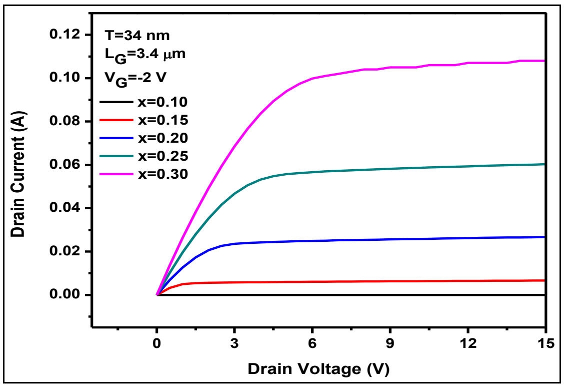

Fig. 24: *The variation of drain current with respect to drain voltage is shown corresponding to the gate voltage (V_G) of -2 volt, gate length (L_G) of 3.4 micron and AlGaN thickness (T) of 34 nm. The variation of drain current is also shown with respect to aluminium mole fraction (x).*

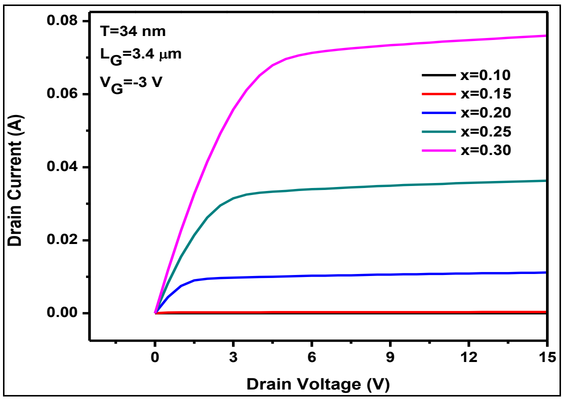

Fig. 25: *The variation of drain current with respect to drain voltage is shown corresponding to the gate voltage (V_G) of -3 volt, gate length (L_G) of 3.4 micron and AlGaN thickness (T) of 34 nm. The variation of drain current is also shown with respect to aluminium mole fraction (x).*

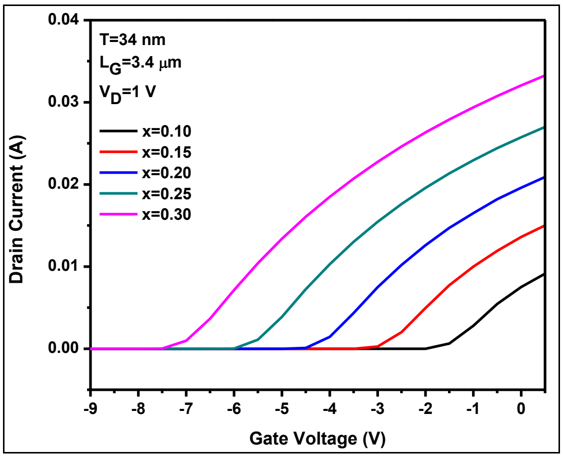

Fig. 26: *The variation of drain current with respect to gate voltage is shown corresponding to the drain voltage (V_D) of 1 volt, gate length (L_G) of 3.4 micron and AlGaN thickness (T) of 34 nm. The variation of drain current is also shown with respect to aluminium mole fraction (x).*

CONCLUSIONS

In our work, total five sets of HEMTs are designed to study the drain characteristics. The drain current is found to be higher at higher drain voltage in single-heterojunction AlGaN/GaN HEMTs. Also, the drain current is found to be higher at higher gate voltage in the designed HEMTs. Further, the drain current is observed as higher due to higher aluminium mole fraction in the HEMTs designed with AlGaN nano-layers. Our work may be helpful to analyze the characteristics of HEMT based sensors in future.

REFERENCES

1. R Brown, A novel AlGaN/GaN based enhancement mode high electron mobility transistor with sub-critical barrier thickness, Thesis, University of Glasgow, 2015.
2. M Charfeddine, H Belmabrouk, MA Zaidi, H Maaref. 2-D theoretical model for current-voltage characteristics in AlGaN/GaN HEMTs. Journal of Modern Physics, Vol. 3 (2012) Pages 881–886.
3. S Mukhopadhyay, S Kalita. Report on the effects of mole fraction, doping concentration, gate length and nano-layer thickness to control the device engineering in the Nanoelectronic AlGaN/GaNHEMTs at 300 K to enhance the reputation of the National Institute of Technology Arunachal Pradesh. Nano Trends, Vol. 19 (2017) Pages 15–47.
4. S Mukhopadhyay. Report on the Novel Electrical Characteristics of Microelectronic High Electron Mobility Transistors to Establish a Low-Cost Microelectronics Laboratory in the National Institute of Technology Arunachal Pradesh. Journal of Semiconductor Devices and Circuits, 4 (2017) Pages 6–28.
5. MK Chattopadhyay, S Tokekar. Thermal model for dc characteristics of AlGaN/GaN HEMTs including self-heating effect and non-linear polarization. Microelectronics Journal, 39 (2008) Pages 1181–1188.
6. MK Chattopadhyay, S Tokekar. Temperature and polarization dependent polynomial based non-linear analytical model for gate capacitance of $Al_mGa_{1-m}N$/GaN MODFET Solid-State Electronics, 50 (2006) Pages 220–227.
7. MK Chattopadhyay, S Tokekar. Analytical model for the transconductance of microwave $Al_mGa_{1-m}N$/GaN HEMTs including nonlinear macroscopic polarization and parasitic MESFET conduction. Microwave and Optical Technology Letters, 49 (2007) Pages 382–389.
8. M Korwal, S Haldar, M Gupta, RS Gupta. Parasitic resistance and polarization-dependent polynomial-based non-linear analytical charge-control model for AlGaN/GaN MODFET for microwave frequency applications. Microwave and Optical Technology Letters, 38 (2003) Pages 371–378.
9. S Khandelwal, N Goyal, TA Fjeldly. A Physics-Based Analytical Model for 2DEG Charge Density in AlGaN/GaN HEMT Devices. IEEE Transactions on Electron Devices, 58 (2011) Pages 3622–3625.
10. S Khandelwal, YS Chauhan, TA Fjeldly. Analytical Modeling of Surface-Potential and Intrinsic Charges in AlGaN/GaN HEMT Devices. IEEE Transactions on Electron Devices, 59 (2012) Pages 2856–2860.

11. S Khandelwal, C Yadav, S Agnihotri, YS Chauhan, A Curutchet, T Zimmer, J. CD Jaeger, N Defrance, TA Fjeldly. Robust Surface-Potential-Based Compact Model for GaN HEMT IC Design. IEEE Transactions on Electron Devices, 60 (2013) Pages 3216–3222.
12. S Khandelwal, TA Fjeldly. A physics based compact model of I-V and C-V characteristics in AlGaN/GaN HEMT Devices. Solid-State Electronics, 76 (2012) Pages 60–66.
13. FM Yigletu, S Khandelwal, TA Fjeldly, B Iniguez. Compact Charge-Based Physical Models for Current and Capacitances in AlGaN/GaN HEMTs. IEEE Transactions on Electron Devices, 60 (2013) Pages 3746–3752.
14. S Ghosh, A Dasgupta, S Khandelwal, S Agnihotri, YS Chauhan. Surface-Potential-Based Compact Modeling of Gate Current in AlGaN/GaN HEMTs. IEEE Transactions on Electron Devices, 62 (2015) Pages 443–448.
15. S Khandelwal, TA Fjeldly. A Physics Based Compact Model for Drain Current in AlGaN/GaN HEMT Devices. Proceedings of the 2012 24th International Symposium on Power Semiconductor Devices and ICs, 3–7 June 2012, Bruges, Belgium, Pages 241–244.
16. SA Ahsan, S Ghosh, K Sharma, A Dasgupta, S Khandelwal, YS Chauhan. Capacitance Modeling in Dual Field-Plate Power GaN HEMT for Accurate Switching Behavior. IEEE Transactions on Electron Devices, 63 (2016) Pages 565–572.
17. A Dasgupta, S Khandelwal, YS Chauhan. Surface Potential Based Modeling of Thermal Noise for HEMT Circuit Simulation. IEEE Microwave and Wireless Components Letters, 25 (2015) Pages 376–378.
18. A Dasgupta, S Khandelwal, YS Chauhan. Compact Modeling of Flicker Noise in HEMTs. Journal of the Electron Devices Society, 2 (2014) Pages 174–178.
19. S Khandelwal, N Goyal, TA Fjeldly. A precise physics-based compact model for 2-DEG charge density in GaAs HEMTs applicable in all regions of device operation. Solid-State Electronics, 79 (2013) Pages 22–25.
20. CC Cheng, YY Tsai, KW Lin, HI Chen, WH Hsu, CW Hung, RC Liu, WC Liu. Pd-Oxide-$Al_{0.24}Ga_{0.76}As$ (MOS) High Electron Mobility Transistor (HEMT)-Based Hydrogen Sensor. IEEE Sensors Journal, 6 (2006) Pages 287–292.
21. X Yu, C Li, ZN Low, J Lin, TJ Anderson, HT Wang, F Ren, YL Wang, CY Chang, SJ Pearton, CH Hsu, A Osinsky, A Dabiran, P Chow, C Balaban, J Painter. Wireless hydrogen sensor network using AlGaN/GaN high electron mobility transistor differential diode sensors. Sensors and Actuators B, 135 (2008) Pages 188–194.

Cite this Article
Avrajyoti Dutta, Sanjib Kalita, Subhadeep Mukhopadhyay. Effects of Drain Voltage, Gate Voltage and Aluminium Mole Fraction on Drain Current in GaN based Single-Heterojunction HEMTs designed with AlGaN Nano-Layers. *Nano Trends: A Journal of Nanotechnology and Its Applications*. 2020; 22(1): 6–14p.