

# Electrical characteristics of AlGa<sub>N</sub>/AlN and AlGa<sub>N</sub>/Ga<sub>N</sub> HEMV•

Payel Sarkar, Arnima Das, Maitreyi Ray Kanjilal

**Abstract**— MESFET and HEMT have very small gate length below 0.5µm and they achieve amplification at a very high frequency range. In particular High-electron-mobility transistors have shown current gain to frequencies greater than 600 GHz and power gain to frequencies greater than 1 THz. These devices have an improved transconductance and carrier saturation velocity due to the decrease in gate to source separation. HEMT offers high power efficiency, greater consistency and broader bandwidth and is thus ideal for use in the THF range (300 GHz to 3 THz) of wireless communication. The electrical response of HEMT formed with AlGa<sub>N</sub>/AlN and AlGa<sub>N</sub>/Ga<sub>N</sub> are compared against each other to find the most suitable heterostructure for the application at high frequency regime.

**Index Terms**— 2DEG, Cutoff frequency, HEMT, High-electron-mobility transistor, Nitride semiconductors, Power devices, THF range, Wireless communication

## 1 INTRODUCTION

High-electron-mobility transistor (HEMT), also known as hetero-structure FET (HFET) or modulation-doped FET (MODFET), is a field-effect transistor incorporating a junction between two materials with different band gaps (i.e. a hetero-junction) as the channel instead of a doped region (as is generally the case for MOSFET). A commonly used material combination is GaAs with AlGaAs, though there is wide variation, depending on the application of the device. Devices incorporating more Indium generally show better high-frequency performance, while in recent years, gallium nitride HEMTs have attracted attention due to their high-power performance. Also another powerful competitor to gallium nitride is the aluminium nitride.

Silicon Carbide (SiC) is chosen as the base material for the HEMT discussed in this paper. SiC is a good substrate for high frequency, high power devices based on GaN as it can handle ten times the power density of a sapphire substrate that is currently being used, due to its extremely high thermal conductivity (4.9W/cm-K). In addition, the epitaxial film qualities of both GaN and AlN are superior when grown on SiC and this should lead the HEMT with better frequency response, higher performance and increased reliability.

AlInN and AlGa<sub>N</sub> are choice materials for forming the heterojunction with AlN and GaN. Since, this would lead to four different combinations, but for simplicity, only the AlGa<sub>N</sub>/AlN and AlGa<sub>N</sub>/Ga<sub>N</sub> pairs are considered in this paper.

## 2 STRUCTURE

### 2.1 Comparison of Semiconductors

It is very useful to do a comparative study of various semi-

conductors to realize the advantages of using SiC as substrate material. The various parameters such as Lattice Constant, Thermal Conductivity and Band Gap have been compared for various semiconductors of group IV, IV-IV and III-V.

TABLE 1  
COMPARISON OF SEMICONDUCTORS

Material	Lattice Constant (Å)	Thermal Conductivity (W/cm-K at ~300K)	Band Gap (eV)
Si	5.43	1.56	1.11
SiC (3C)	4.36	3.6	2.3
SiC (4H)	3.07	3.7	3.3
SiC (6H)	3.07	4.9	3.0
GaN	3.18 a	2.0	3.44
AlN	3.11 a	3.2	6.28
AlInN	3.11, 3.54, 4.98, 5.70	-	0.7 – 6.28
AlGa <sub>N</sub>	3.14 apprx	-	3.44 – 6.28
GaAs	5.65	0.54	1.43
AlGaAs	5.63	0.55 – 2.12	1.42 – 2.16
GaInAs	5.86	0.05	0.74
Sapphire	4.76	0.35	9.9

It can be easily noted from the table the relative band gap differences that would later help in studying 2DEG formation and other characteristics. From the above table it can be very well inferred why GaAs/AlGaAs is the choice combination for fabricating HEMT. It is also evident from the data presented that at a higher power range the performance of GaAs would be significantly poorer to GaN or AlN. Sapphire, upon which

- Payel Sarkar is currently pursuing masters degree program in electronics and communication engineering in Narula Institute of Technolgy, West Bengal, India, PH-9432092349. E-mail: payelsarkar.sarkar@gmail.com
- Arnima Das is Assistant Professor, ECE at Narula Institute of Technolgy, West Bengal, India, PH-9051884445. E-mail: arnimaz@gmail.com
- Dr. Maitreyi Ray Kanjilal is Professor & Head of Department, ECE, at Narula Institute of Technolgy, West Bengal, India. She is also member of IEEE, ISTE, IETE. PH-9433208610. E-mail: mr.kanjilal@gmail.com

the GaN/AlN epitaxial is currently grown, has a very low thermal conductivity and higher band gap. Also the lattice mismatch percentage to GaN or AlN is very high. In this regard SiC is a very promising substitute which has almost ten times higher thermal conductivity and lattice constant matching with low band gap material. Also the crystal defect on a SiC will be minimized as only a very thin slice of it is needed to be used.

It has been studied how the low energy band gap difference AlGaIn/GaN heterostructure differs from the high band gap difference AlGaIn/AlN HEMT while forming the 2DEG. The 2DEG formation is an intricate part of working principle of HEMT, which is also called the heart of the device.

### 2.2 2DEG Formation

The 2DEG formation of the combination pairs concerned is different from each other. The typical device conception is shown along with the 2DEG formation to understand this better.

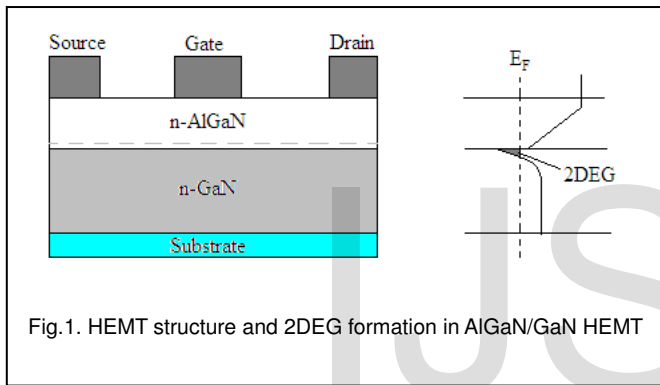


Fig.1. HEMT structure and 2DEG formation in AlGaIn/GaN HEMT

This formation in the diagram is only a schematic study for preliminary tests.

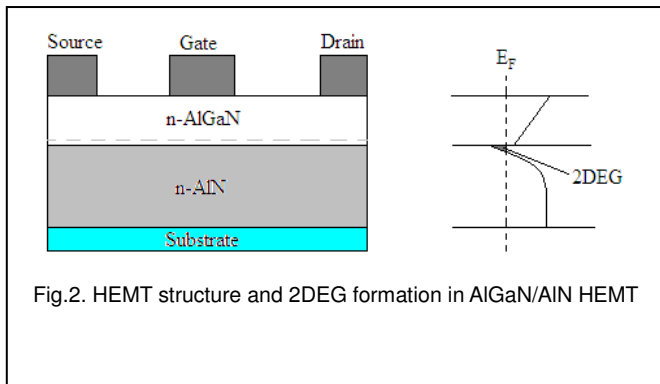


Fig.2. HEMT structure and 2DEG formation in AlGaIn/AlN HEMT

## 3 THEORY

### 3.1 Drain Characteristics

The electrical response of a device can be analysed initially by studying its output characteristics. Here at the beginning the variations of drain current ( $I_D$ ) as a function of drain to source voltage ( $V_{DS}$ ), for a constant gate to source voltage ( $V_{GS}$ ), have

been reported. The drain current flowing through the channel in HEMT is contributed by electrons and the two-dimensional electron gas takes the main role to control the current. The drain current is expressed as [1]

$$I_D = qn_s v_{sat} Z \tag{1}$$

Where,  $n_s$  is the sheet carrier density,  $v_{sat}$  is the saturation velocity of the electrons in the channel and  $Z$  is the gate width. To study the variation of drain current with drain to source voltage eqn. (1) is expressed as

$$I_D = f(V_{DS}, V_{GS}) \tag{2}$$

### 3.2 Transfer Characteristics

Transconductance is an important characteristic of active device which controls the electrical performance. The transconductance is expressed as

$$g_m = \left. \frac{\partial I_{DS}}{\partial V_{GS}} \right|_{V_{DS}} \tag{3}$$

Using the relation of  $v_{sat}$  with  $g_m$  in the equation of  $I_D$  the transconductance has been studied for the different heterostructures.

### 3.3 Cutoff Frequency

Cutoff frequency is another important parameter which has been studied to find out the frequency response of HEMT for different material combinations. Cutoff frequency can be expressed as [1]

$$f_t = \frac{g_m}{2\pi(C_{GS} + C_{GD})} \tag{3}$$

## 4 RESULTS AND ANALYSIS

The results obtained by using the above relation for for both AlGaIn/AlN and AlGaIn/GaN HMTs have been shown in Figs.3-7. The only factor differentiating the results for different

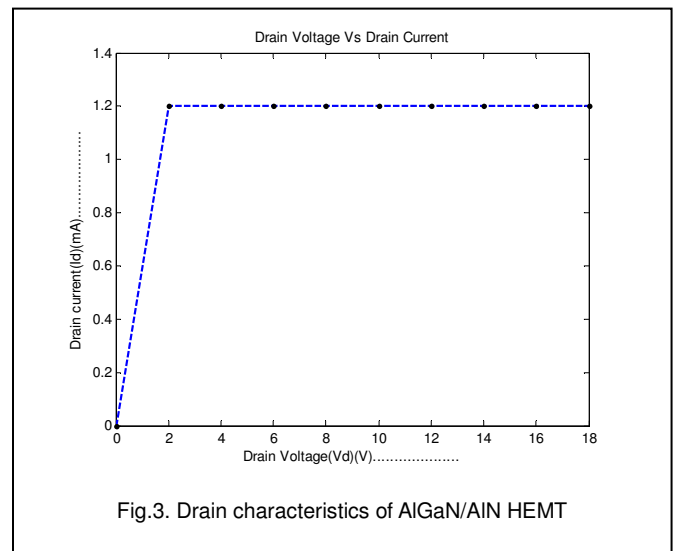


Fig.3. Drain characteristics of AlGaIn/AlN HEMT

heterostructures is the materials. The gate to source capacitance is the main concerning factor in the high frequency performance of a FET. In AlGa<sub>N</sub>/Ga<sub>N</sub> the value of  $C_{GS}$  ( $= 1.45 \text{ pF}$ ) is higher than in AlGa<sub>N</sub>/Al<sub>N</sub> ( $C_{GS} = 0.7 \text{ pF}$ ) [1]. The sheet carrier density which could be much higher for AlGa<sub>N</sub>/Al<sub>N</sub> combination due to the higher band gap of Al<sub>N</sub>, but here it is kept at  $1 \times 10^{13} \text{ cm}^{-2}$  for both. The effective gate length and gate width are considered respectively at  $0.29 \mu\text{m}$  and  $0.1 \text{ cm}$ .

The drain characteristic is plotted considering the saturation current  $1.2 \text{ A/mm}$  at  $V_{GS} = 0$ .

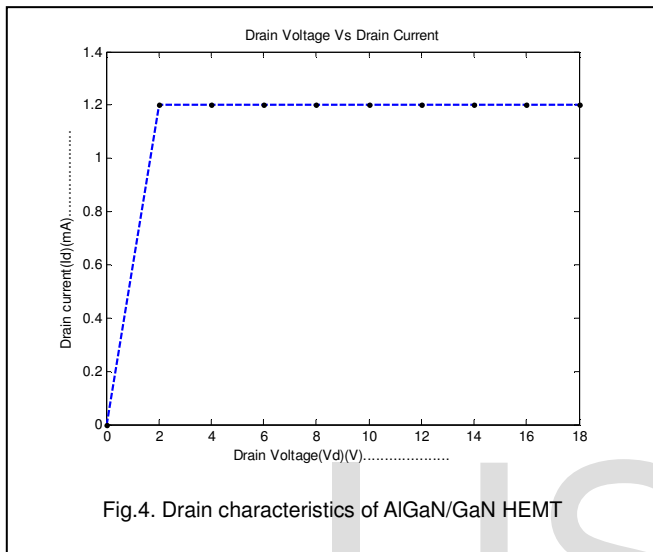


Fig.4. Drain characteristics of AlGa<sub>N</sub>/Ga<sub>N</sub> HEMT

Similar results are obtained in both AlGa<sub>N</sub>/Al<sub>N</sub> and AlGa<sub>N</sub>/Ga<sub>N</sub> ( Fig 3 and Fig 4 ) because the sheet current density has been considered same for simplicity.

The transfer characteristics have been shown in Fig.5 and Fig.6 using the previously assumed values.

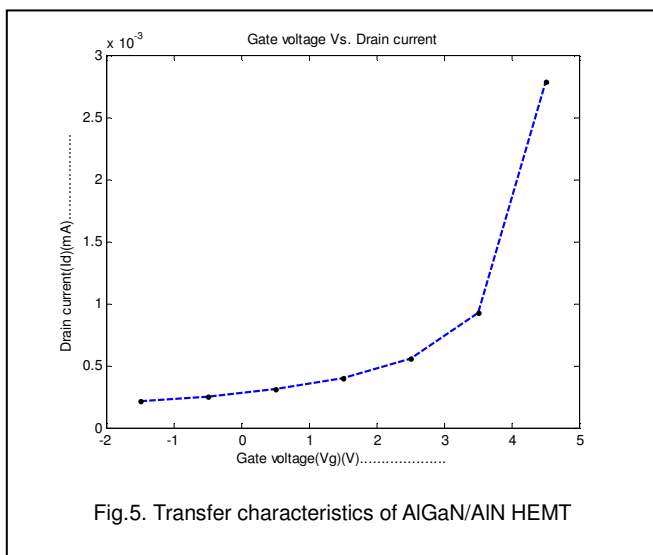


Fig.5. Transfer characteristics of AlGa<sub>N</sub>/Al<sub>N</sub> HEMT

The considerable difference between the transfer characteristics of the AlGa<sub>N</sub>/Al<sub>N</sub> and AlGa<sub>N</sub>/Ga<sub>N</sub> HEMT may be noticed here. There is a considerable large drain current for same gate bias in

case of Al<sub>N</sub> (Fig 6) than the Ga<sub>N</sub> counterpart (Fig 7). This is because of the higher band gap of Al<sub>N</sub>. Also, it has been observed that the drain characteristics are almost similar for both the material combinations discussed above.

The varying transconductance of the two devices yielded interesting results in the study of cut-off frequency. Several plots have been drawn to study and compare the nature of the cut-off frequency in the two material combinations.

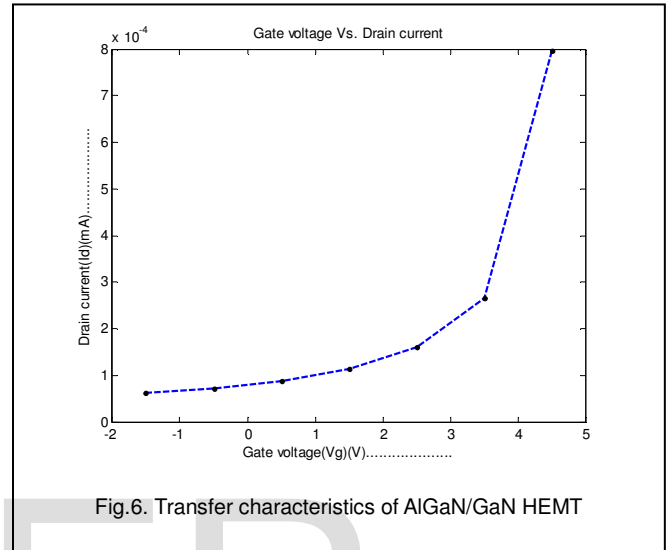


Fig.6. Transfer characteristics of AlGa<sub>N</sub>/Ga<sub>N</sub> HEMT

Figs. 7 - 10 represent the variation of cut-off frequency as a function of transconductance and gate to source voltage by using the equation (4).

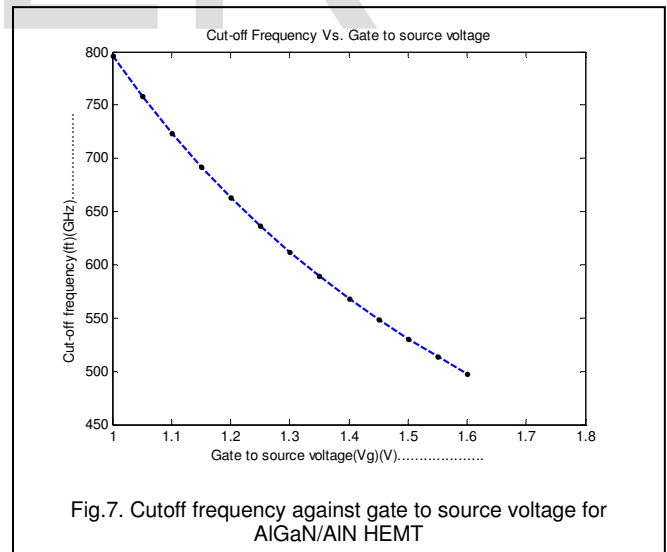


Fig.7. Cutoff frequency against gate to source voltage for AlGa<sub>N</sub>/Al<sub>N</sub> HEMT

The nature of the graphs produced reinstates the theory and definition of transconductance overall. The variation of gate to source capacitance is responsible for the variation of  $f_t$ .

Also it is noticeable that the plot for cut-off frequency against transconductance is almost linear because they bear the linear relationship. Where as, the variation of cut-off frequency with the gate to source voltage is slightly exponential in nature which is

relevant with equation (4) as  $C_{GS}$  depends on  $V_{GS}$ .

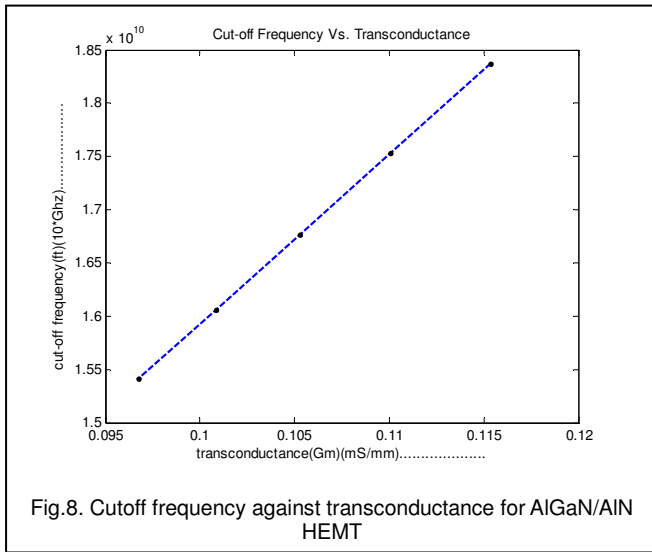


Fig.8. Cutoff frequency against transconductance for AlGaIn/AlN HEMT

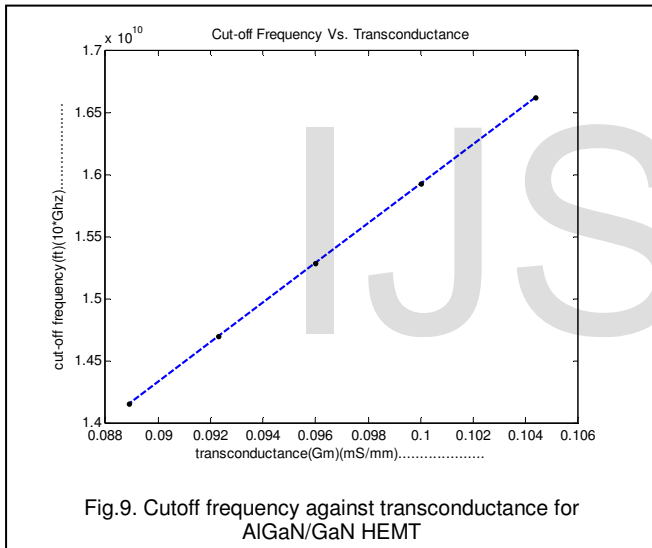


Fig.9. Cutoff frequency against transconductance for AlGaIn/GaN HEMT

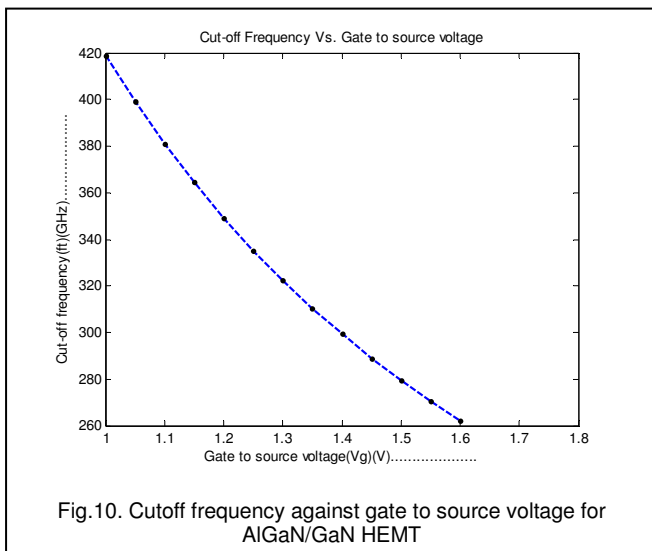


Fig.10. Cutoff frequency against gate to source voltage for AlGaIn/GaN HEMT

## 5 CONCLUSION

HEMT becomes a promising device in the high frequency regime of the latest ventures of science and engineering, so there is lot of studies to be done on this, both theoretically and experimentally.

## ACKNOWLEDGMENT

The authors wish to thank the entire department of Electronics and Communications engineering, Narula Institute of Technology for their support and encouragement on this ongoing research. A special thank for Prof. Kaushik Sarkar for his help on some special MATLAB functions and programs. Also the authors are grateful to Dr. Moumita Mukherjee, Scientist B - CMSDS Kolkata for her suggestion in various points.

## REFERENCES

- [1] O. Jardel, G. Callet, J. Dufraisse, M. Piazza, N. Sarazin, E. Chartier, M. Oualli, R. Aubry, T. Reveyrand, J. C. Jacquet, M. A. Di Forte Poisson, E. Morvan, S. Piotrowicz and S. L. Delage, "Electrical Performances of AlInN/GaN HEMTs. A comparison with AlGaIn/GaN HEMTs with similar technological progress," *International Journal of Microwave and Wireless Technologies*, Volume 3, Issue 3, pp. 301-309, June 2011.
- [2] Mukunda B. Das, "A High Aspect Ratio Design Approach to Millimeter-Wave HEMT Structures," *IEEE Transactions on Electron Devices*, vol. ED-32, no. 1, pp. 11-17, Jan 1985
- [3] Saeroonter Oh and H. S. Philip Wong "Effect of Parasitic Resistance and Capacitance on Performance of InGaAs HEMT Digital Logic Circuits," *IEEE Transactions on Electron Devices*, vol. 56, no. 5, pp. 1161-1164, May 2009
- [4] Giorgi Aroshvili, "GaN HEMT and MMIC Design and Evaluation," Master's Thesis, Dept. of Technology and Built Environment, University of Gävle, Sweden, Sept. 2008
- [5] Dr. E. N. Ganesh, "Simulation of GaAs MESFET and HEMT Devices for RF Applications," *International Journal of Emerging Trends and Technology in Computer Science*, Volume 2, Issue 1, pp. 123-128, Feb. 2013. ISSN 2278-6856
- [6] Wang Xin-Hua, Zhao Miao, Liu Xin-Yu, Pu Yan, Zheng Ying-Kui and Wei Ke, "The Physical Process Analysis of the Capacitance-Voltage Characteristics of AlGaIn/AlN/GaN high electron mobility Transistors," , Volume 19, No. 9, pp. 097302-1-7, 2010.
- [7] R. Gaska, Q. Chen, J. Yang, A. Osinsky, M Asif Khan and M. S. Shru, "High-Temperature Performance of AlGaIn/GaN HFET's on SiC Substrates," *IEEE Electron Device Letters*, vol. 18, no. 10, pp. 492-494, Oct 1997
- [8] Wataru Saito, Yoshiharu Takada, Masahiko Kuraguchhi, Kunio Tsuda and Ichiro Omura, "Recessed-Gate Structure Approach Toward Normally Off High-Voltage AlGaIn/GaN HEMT for Power Electronics Applications," *IEEE Transactions on Electron Devices*, vol. 53, no. 2, pp. 356-362, Feb 2006
- [9] Sima Dimitrijevic, *Semiconductor Devices*. Oxford University Press, First Indian Edition 2010, pp. 536-540, 2010