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A Comparative Analysis of Dissimilar High Electron Mobility Transistors and Applications

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***Abstract*—High Electron Mobility Transistors (HEMTs) are advanced semiconductor devices that have gained significant attention in recent years due to their exceptional performance in high-frequency and high-power applications. This comparative analysis investigates and compares the characteristics, material compositions, and applications of dissimilar HEMTs. The study focuses on two primary types of HEMTs: GaN HEMTs and InP HEMTs. Overall, this comparative analysis contributes to understanding dissimilar HEMTs and highlights their diverse applications, paving the way for advancements in high-performance semiconductor devices and enabling the development of innovative technologies in multiple industries.**

Keywords—GaN HEMTs, InP HEMTs, material compositions, high-power application, semiconductor devices.

I. INTRODUCTION

High Electron Mobility Transistors (HEMTs) have emerged as crucial semiconductor devices with exceptional performance characteristics, particularly in high-frequency and high-power applications. HEMTs are a type of field-effect transistor designed to provide high electron mobility in the channel region, resulting in enhanced device performance[1]. HEMTs are typically fabricated using compound semiconductors, such as Gallium Nitride (GaN), Indium Phosphide (InP), or their combinations, as these materials offer superior properties compared to traditional silicon-based transistors. The unique material composition and device structure of HEMTs contributes to their remarkable performance advantages[2].

The critical characteristic of HEMTs is their high electron mobility, which refers to the ability of electrons to move through the channel region with minimal resistance. This increased mobility allows for efficient and rapid electron flow, enabling HEMTs to operate at high frequencies. HEMTs exhibit superior performance compared to other transistor technologies, such as Metal-Oxide-Semiconductor Field-Effect Transistors (MOSFETs), regarding power handling capabilities, power efficiency, and frequency operation[3]. The channel region in HEMTs is typically a heterostructure consisting of multiple layers of different semiconductor materials. This heterostructure design facilitates electron confinement and provides a pathway for efficient electron transport. HEMTs can achieve high electron mobility and excellent device performance by carefully engineering the heterostructure and material compositions[4].

HEMTs find extensive applications in various industries and technologies. They are widely utilized in wireless communication systems, including mobile networks, satellite communications, and radar systems, where their high-frequency operation and power efficiency enable high-speed data transmission and improved signal reception. HEMTs are also essential in power electronics, such as power supplies and electric vehicle systems, as their high-power density and efficiency contribute to enhanced energy conversion and reduced losses[5]. In addition, HEMTs play a crucial role in optoelectronic devices and systems. They are utilized in optical communication systems, such as fiber optic networks, where high-speed operation enables high-bandwidth data transmission. HEMTs also find applications in microwave amplifiers, high-speed digital circuits, and other areas requiring high-frequency signal processing and amplification[6].

The continuous advancement in HEMT technology, including developing novel materials and device structures, holds promise for further improvements in device performance and expanded applications. Researchers and engineers continue to explore the potential of HEMTs in pushing the boundaries of high-frequency, high-power, and high-efficiency electronic systems. Overall, HEMTs represent a significant breakthrough in semiconductor technology, offering superior performance in high-frequency and high-power applications. Their unique characteristics and applications make them a key focus of research and development, driving advancements in various industries and enabling the realization of innovative electronic systems[7]. This paper includes an Introduction, Literature survey, Device Architecture, Working and Performance analysis, application, and Conclusion.

II. LITERATURE SURVEY

HEMTs have witnessed significant research and development efforts in recent years. Numerous studies have investigated the properties and applications of various HEMTs, with particular emphasis on GaN and InP-based devices. Studies on GaN HEMTs have highlighted their superior power handling capabilities, high breakdown voltage, and excellent thermal conductivity. Researchers have demonstrated the advantages of GaN HEMTs in power electronics, where they offer high efficiency and power density, making them suitable for applications such as power amplifiers, power supplies, and electric vehicles. Furthermore, GaN HEMTs have been extensively explored in the field of wireless communication systems, including 4G, 5G, and beyond, due to their high-frequency operation and power efficiency[8]. InP HEMTs have also garnered considerable attention due to their outstanding high-frequency performance and low noise characteristics.

Researchers have investigated the potential of InP HEMTs in optical communication systems, where their high-speed operation and low power consumption make them suitable for applications such as photodetectors and optical modulators. InP HEMTs have also been explored in microwave amplifiers and high-speed digital circuits, showcasing their ability to operate at extremely high frequencies. The comparative analysis presented in this study builds upon the existing literature by providing a comprehensive overview and comparison of dissimilar HEMTs. It aims to bridge the knowledge gap by delving into the material compositions, structural differences, and performance metrics of GaN HEMTs and InP HEMTs [9].

By evaluating parameters such as power handling capabilities, electron mobility, operating frequencies, and efficiency, this study aims to offer valuable insights into the respective strengths and weaknesses of these HEMT technologies. Furthermore, this analysis explores the applications of dissimilar HEMTs in various industries. GaN HEMTs have found extensive use in wireless communication systems, radar systems, satellite communications, and power electronics, enabling high-speed data transmission, improved signal reception, and efficient power conversion.

InP HEMTs have proven valuable in optical communications, microwave amplifiers, and high-speed digital circuits, facilitating high-speed signal processing and data transmission. By examining the characteristics and applications of dissimilar HEMTs, this study aims to provide a reference for researchers, engineers, and industry professionals in selecting the most suitable HEMT technology for specific high-frequency and high-power applications [10]. The findings of this comparative analysis will contribute to the advancement of HEMTs and the development of innovative technologies across multiple industries.

III. Device Architecture of HEMTs

Several types of High Electron Mobility Transistors (HEMTs) are based on their material composition and device structure. Here are some of the commonly known types:

A. GaN HEMTs: These are HEMTs made using Gallium Nitride (GaN) as the semiconductor material shown in Fig. 1. GaN HEMTs have gained significant attention recently due to their excellent power handling capabilities, high breakdown voltage, and high-speed operation. They are widely used in power electronics, RF amplifiers, and high-frequency applications [11].

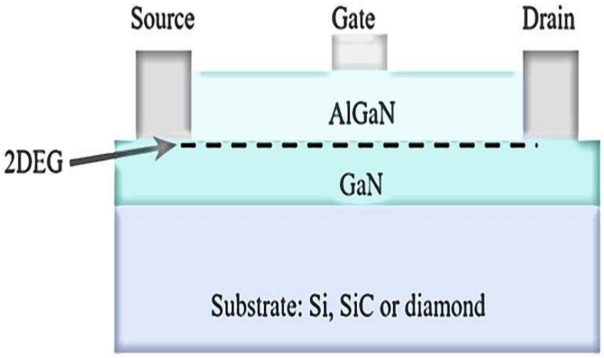

Fig.1. Basic structure of GaN HEMT [11]

B. AlGaN/GaN HEMTs: These HEMTs are based on a heterostructure of Aluminum Gallium Nitride (AlGaN) and Gallium Nitride (GaN) shown in Fig. 2.

The AlGaN layer acts as a barrier to enhance the electron confinement in the channel region, improving the device's performance. AlGaN/GaN HEMTs are particularly suitable for high-power, high-frequency applications[12].

AlGaN/GaN High Electron Mobility Transistors (HEMTs) are a type of HEMT that utilize a heterostructure composed of Aluminum Gallium Nitride (AlGaN) as the barrier layer and Gallium Nitride (GaN) as the channel layer. This specific heterostructure design offers several advantages and unique characteristics for high-performance transistor applications. Here are some key explanations about AlGaN/GaN HEMTs:

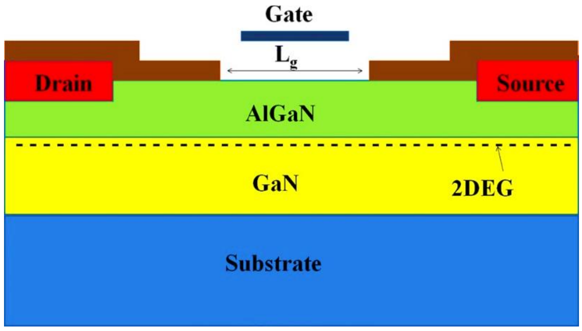

Fig. 2 AlGaN/GaN Based HEMT[12]

Table:I Device Parameters for AlGaN/GaN HEMT.

Parameters	Value
AlGaN – Doping	10^{17}cm^{-3}
Carrier density	10^{11}/cm^2
Drift velocity	1.15E^5
Electric field	160E^5
Charge density	1.4*10^{-19}
Channel Length	100 nm
Barrier and Spacer layer thickness	25 nm

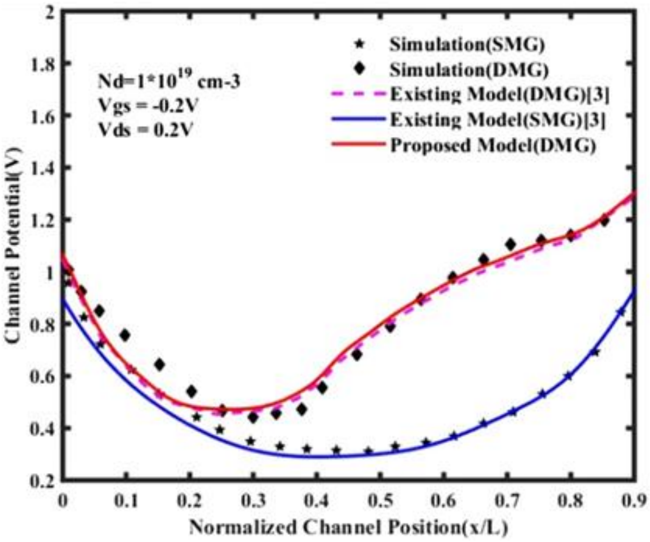

Fig. 3. Channel Potential Vs. Normalized Channel Position of AlGaN/GaN HEMT[13]

Fig. 3 The curve illustrates how the wide bandgap of the AlGaN barrier layer enhances the effective channel potential compared to the conventional HEMT. While the source side remains the same as the SMG, the drain end experiences an increased potential due to the interface of two metals in the gates. This is because the work function in M1 is higher than that in M2, necessitating a higher voltage to facilitate electron flow on this side. Consequently, the increase in drain voltage reduces DIBL (Drain-Induced Barrier Lowering).

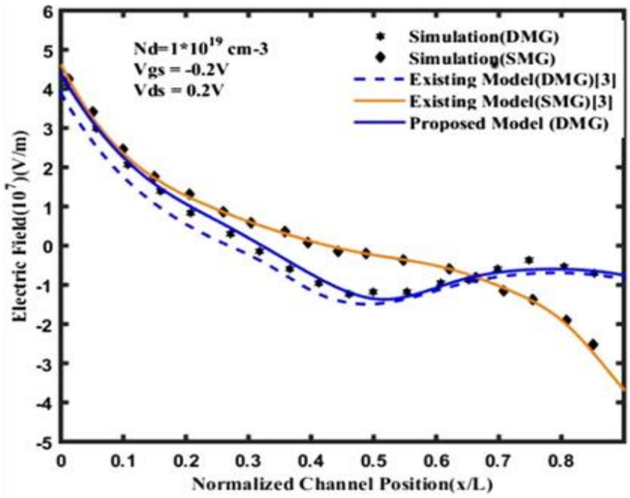

Fig. 4. Electric field Vs. Normalized Channel Position of AlGaN/GaN HEMT[13]

Fig. 4 demonstrates that the proposed model attains the highest electric field, corresponding to the maximum carrier density. In the case of the SMG device, an augmented electric field on the source channel side enhances carrier transport, while a singular peak on the drain side amplifies electron acceleration, resulting in maximum drift velocity and the occurrence of the hot carrier effect. However, this effect is mitigated in the DMG due to the gate's two-metal interface. As a result, the hot carrier effect is reduced, leading to a decrease in drift velocity on the drain side.

a) *Heterostructure Design:* AlGaN/GaN HEMTs consist of a layered structure where the AlGaN layer acts as the barrier and the GaN layer serves as the conducting channel. The AlGaN layer has a wider bandgap than GaN, acting as a barrier to confine the electrons within the GaN channel.
b) *High Electron Mobility:* GaN is known for its excellent electron mobility, which allows for fast electron transport and high-frequency operation. The combination of GaN as the channel material and AlGaN as the barrier material in AlGaN/GaN HEMTs enables high electron mobility, contributing to their high-speed and high-frequency capabilities.
c) *High Power Handling:* The AlGaN/GaN HEMTs exhibit excellent power handling capabilities due to the wide bandgap of GaN and the efficient electron transport within the device. This makes them suitable for high-power applications, such as power electronics, where they can handle high voltages and currents efficiently.
d) *High Breakdown Voltage:* The AlGaN/GaN heterostructure provides a high breakdown voltage, allowing the transistors to withstand high voltages without breakdown or damage. This characteristic is crucial for applications requiring high-voltage operation and robustness.
e) *Low On-Resistance:* AlGaN/GaN HEMTs offer low on-resistance, which results in reduced power losses and improved energy efficiency. The combination of the high electron mobility in GaN and the heterostructure design helps to minimize resistance and enhance device performance.
f) *Wide Bandgap Material:* The wide bandgap of GaN makes AlGaN/GaN HEMTs suitable for high-temperature operation, as they can withstand higher temperatures compared to traditional silicon-based transistors. This characteristic is advantageous for applications where thermal management is critical, such as power electronics and high-temperature environments.

AlGaN/GaN HEMTs offer a unique combination of high electron mobility, high power handling, low on-resistance, and high breakdown voltage. These characteristics make them promising devices for a wide range of applications, particularly those requiring high-speed, high-power, and high-frequency operation. Ongoing research and development continue to optimize the performance of AlGaN/GaN HEMTs and explore their potential in emerging technologies.

C. InP HEMTs: These HEMTs are based on Indium Phosphide (InP) as the semiconductor material [13]. InP HEMTs offer excellent high-frequency performance, low noise characteristics, and high electron mobility. They are commonly used in high-speed digital circuits, microwave amplifiers, and optical communication systems. The device architecture is shown in Fig. 5.

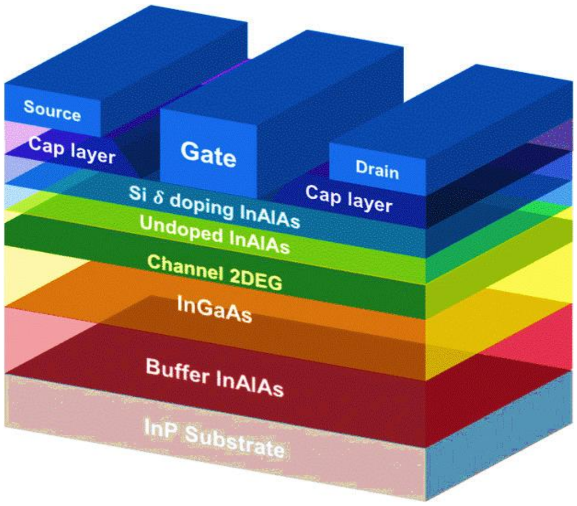

Fig. 5 Basic structure of InP HEMT[13]

D. InAlAs/InGaAs HEMTs: These HEMTs utilize a heterostructure consisting of Indium Aluminum Arsenide (InAlAs) and Indium Gallium Arsenide (InGaAs), shown in Fig. 6. The combination of these materials provides high electron mobility and makes them suitable for high-frequency applications, including wireless communication systems and microwave amplifiers[14].

InAlAs/InGaAs High Electron Mobility Transistors (HEMTs) are a type of HEMT that utilize a heterostructure consisting of Indium Aluminum Arsenide (InAlAs) as the barrier layer and Indium Gallium Arsenide (InGaAs) as the channel layer. These devices offer unique characteristics and advantages for high-performance transistor applications. Here are some explanations about InAlAs/InGaAs HEMTs:

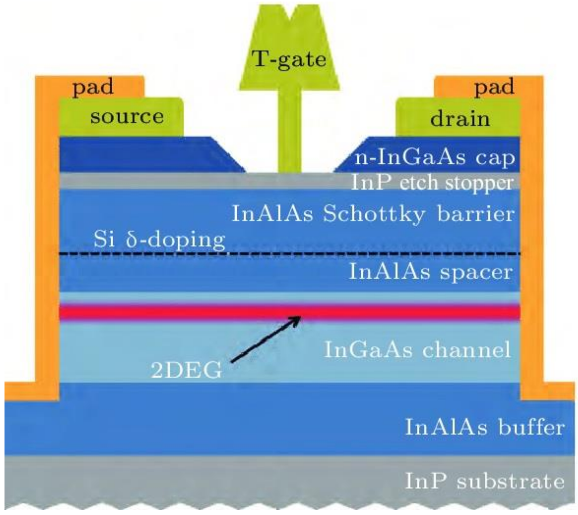

Fig.:6 InAlAs/InGaAs Based HEMT[14]

DC characteristics - The DC properties were evaluated at room temperature. Fig. 7 depicts the I-V characteristics of the HEMT with an Lg of 97 nm and a Wg of 1.5 × 40 µm, also at room temperature. The V_{GS} was incremented from -0.6 V to 0.4 V in steps of +0.1 V, while V_{DS} ranged from 0 V to 1.7 V. The HEMT exhibits excellent pinch-off characteristics, which can be attributed to the improved gate modulation achieved through the recessed gate technique. Furthermore, the presence of the InP etching-stopper layer as a surface passivation strategy greatly diminishes the kink effect in the device. This passivation technique effectively aligns the Fermi level with the conduction band minimum, resulting in a high initial carrier density within the channel. Consequently, the impact of ionization and traps within the buffer or barrier is significantly reduced.

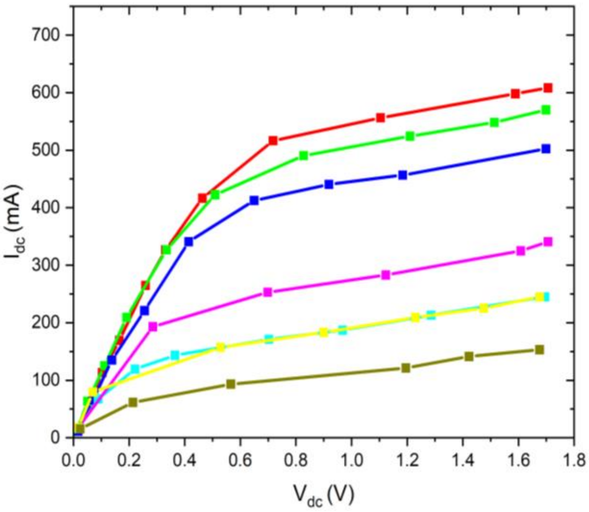

Fig. 7 Drain current output characteristics of the InAlAs/InGaAs HEMT

Fig. 8 illustrates the extrinsic transconductance and drain current of the HEMT under a bias condition of V_{DS} = 1.6 V. The pinch-off voltage is approximately -0.4 V. At V_{GS} = -0.2 V, the HMET reaches a maximum extrinsic transconductance (gm. max) of 1031 mS/mm. The device exhibits a measured full channel current of 624 mA/mm at V_{GS} = 0.3 V and I_{DSS} of 296 mA/mm at V_{GS} = 0 V.

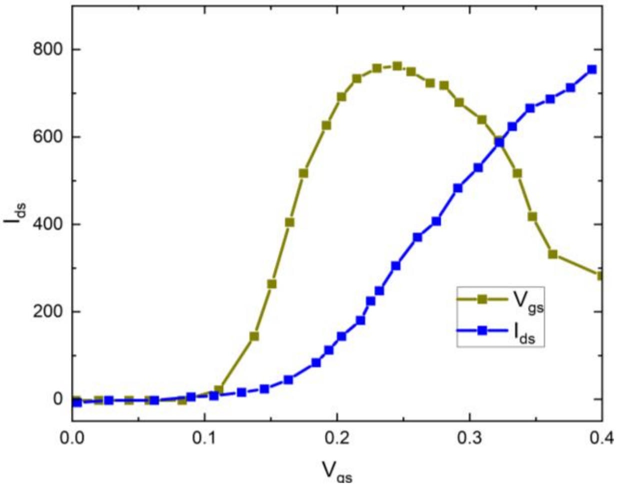

Fig. 8 I_D - Gate bias of the InAlAs/InGaAs HEMT (V_{DS} = 1.6 V).

a) *Low Indium Composition in Channel:* The InGaAs channel layer typically has a low indium composition to reduce strain and lattice mismatch with the substrate. This helps to maintain high electron mobility and minimize defects in the channel, improving device performance.

b) *High Voltage Operation:* InAlAs/InGaAs HEMTs offer high voltage operation capabilities due to the wide bandgap of the InAlAs barrier layer. The wide bandgap allows the device to withstand higher voltages without breakdown or damage, making them suitable for high-voltage applications.

c) *High-Frequency Applications:* InAlAs/InGaAs HEMTs are well-suited for high-frequency applications such as wireless communication systems, satellite communication, radar systems, and high-speed digital circuits. Their high electron mobility and low parasitic capacitance enable efficient high-frequency signal processing.

d) *Emerging Technologies:* InAlAs/InGaAs HEMTs have gained attention in emerging technologies such as terahertz electronics and quantum computing. Their unique properties make them promising candidates for these advanced applications, where high-speed and low-noise performance are critical.

E. ZnO HEMTs: Zinc Oxide (ZnO)-based High Electron Mobility Transistors (HEMTs) are semiconductor devices that utilize ZnO as the channel material. The theory behind ZnO-based HEMTs involves the understanding of the ZnO material properties, heterostructure design, and device operation [15].

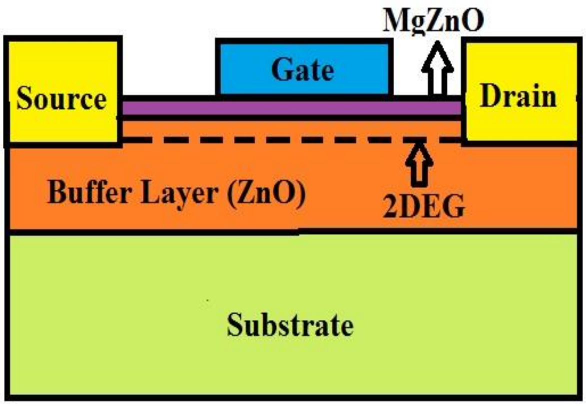

Fig.:9 Basic structure of ZnO HEMT

a) *ZnO Material Properties:* ZnO is a wide-bandgap semiconductor with unique properties that make it suitable for HEMT applications. It has a large exciton binding energy, high electron mobility, and a wide bandgap, which allows for high-temperature operation and efficient power handling.

b) *Heterostructure Design:* The ZnO-based HEMTs typically have a heterostructure design similar to other HEMTs. It involves the growth of ZnO layers on a suitable substrate, such as Sapphire or Silicon. The heterostructure consists of multiple layers, including the ZnO channel layer, barrier layer, and source/drain contacts.

c) *ZnO Channel Layer:* The ZnO channel layer acts as the conductive region where electrons flow. It is typically a thin layer of ZnO with high electron mobility. The quality and purity of the ZnO layer are critical for achieving high device performance.

d) *Barrier Layer:* The barrier layer is typically made of a different material with a wider bandgap than ZnO, such as MgZnO or BeZnO. It serves as a barrier to confine the electrons within the ZnO channel, preventing them from escaping and improving the device performance.

e) *Source and Drain Contacts*: Ohmic metal contacts are deposited on the ZnO layer to provide electrical connections for the source and drain regions. These contacts enable the injection and extraction of electrons into and out of the ZnO channel.

f) *Gate:* The gate electrode is placed on top of the barrier layer, forming a metal-insulator-semiconductor (MIS) structure. The gate voltage controls the conductivity of the ZnO channel by modulating the electron density, similar to other HEMTs. It allows for the modulation of current flow and acts as the primary control element of the device.

IV. WORKING AND PERFORMANCE METRICS OF HEMT

HEMTs are semiconductor devices that consist of heterojunctions formed by combining materials with different bandgaps. In a heterojunction, the materials' conduction band and valence band must bend to achieve a continuous energy level. The material with a wider bandgap is typically doped with donor atoms or exhibits polarization charge (in the case of GaN-based HEMTs), resulting in excess electrons in its conduction band[16].

Conversely, the material with a narrower bandgap has conduction band states with lower energy. As a result, electrons diffuse from the wide bandgap material to the adjacent lower bandgap material, seeking states with lower energy. This electron movement leads to a change in potential and the creation of an electric field between the materials.

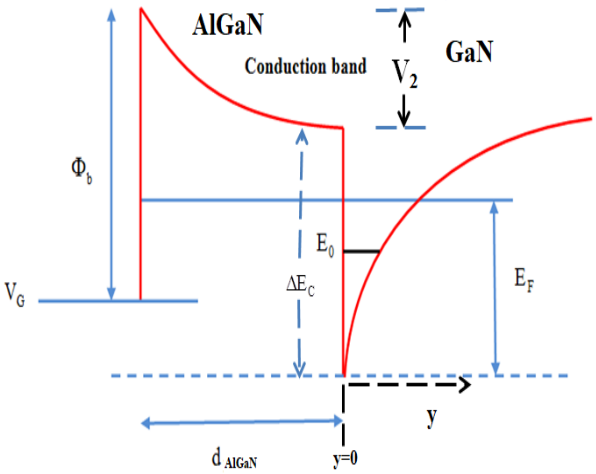

Fig. 10 Energy Band Diagram of HEMT[18]

The induced electric field causes the drifted electrons to return to the conduction band of the wide bandgap material. The processes of drift and diffusion continue until they reach a state of equilibrium, establishing a junction similar to a p-n junction. It is important to note that the narrow bandgap material, which is undoped, now possesses an excess of majority charge carriers, allowing for high switching speed. Furthermore, the absence of donor atoms in the undoped narrow bandgap material prevents scattering and ensures high electron mobility[17].

In summary, HEMTs exploit the formation of heterojunctions between dissimilar bandgap semiconductors. The movement of electrons between materials creates an electric field, establishing a junction and enabling high-speed switching. The undoped narrow bandgap material exhibits high mobility due to the absence of donor atoms, contributing to the overall performance of HEMTs.

V. Comparative analysis of dissimilar HEMTs

In this section, we describe the calculation of various HEMT surface potentials with different gate voltages and the comparative analysis of drain current (I_D) from experimental models.

TABLE II: Surface Potential Calculation with various Gate Voltage

Gate Voltage (V_G)	**AlGaN/GaN HEMT**	**InAlAs/InGaAs HEMT**	**MgZnO/ZnO HEMT**
-4	-0.7745	-0.9917	-0.8816
-3.5	-0.2718	-0.4933	-0.3523
-3	-0.0316	-0.0531	-0.0426
-2.5	0.0791	0.0967	0.0856
-2	0.1683	0.1841	0.1745
-1.5	0.2318	0.2572	0.2475
0	0.2952	0.2893	0.2586
0.5	0.3587	0.3869	0.3654

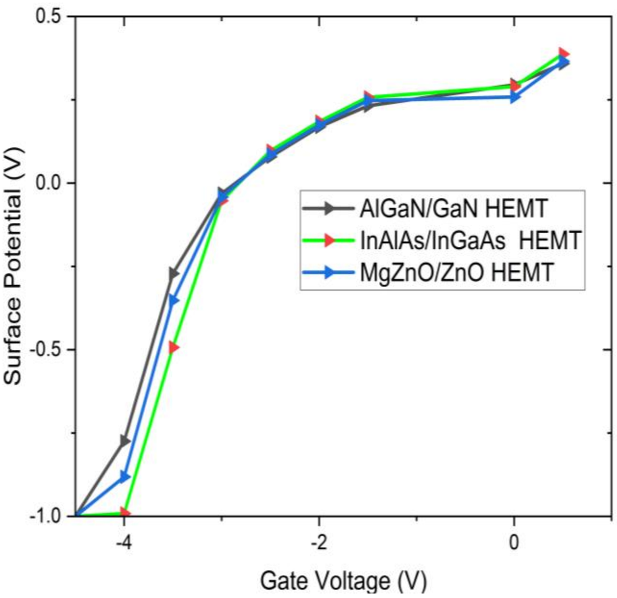

Fig. 11. Comparison graph of various Gate Voltage inputs Vs. Surface Potential

TABLE III: Drain current calculation at V_{GS}=1.6 V with various types of HEMT

V_D (V)	**AlGaN/GaN HEMT**	**InAlAs/InGaAs HEMT**	**MgZnO/ZnO HEMT**
0	0	0	0
0.5	50	66	60
1	102	119	110
1.5	128	158	140
2	135	184	165
2.5	150	198	178
3	170	203	180
3.5	154	205	184
4	164	207	184.5
4.5	168	208	186
5	172	209	186.5
5.5	165	210	190
6	185	211	200

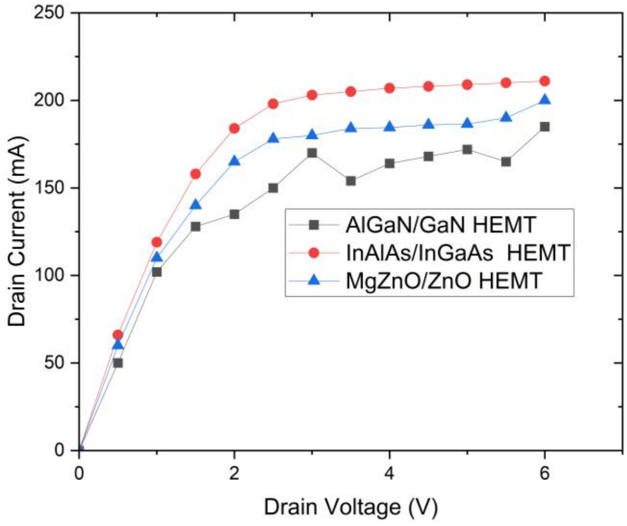

Fig. 12. Drain Voltage vs. Drain Current at Vgs=-1.6 V

VI. Applications of HEMTs

a) *Wireless Communication Systems:* HEMTs are widely used in mobile communication networks, including 4G, 5G, and beyond. They are employed in power amplifiers and low-noise amplifiers, enabling high-speed data transmission and improved signal reception.

b) *Radar Systems:* HEMTs find applications in radar systems used for defense, aviation, and weather monitoring. They provide high-power amplification and low-noise performance, enhancing the detection and range capabilities of radar systems.

c) *Satellite Communications:* HEMTs are utilized in satellite communication systems due to their ability to operate at high frequencies and withstand the harsh space environment. They enable efficient signal amplification and reliable data transmission in satellite communication networks.

d) *Power Electronics:* GaN HEMTs are increasingly used in power conversion applications, such as power supplies, electric vehicles, and renewable energy systems. Their high power density and efficiency make them suitable for high-frequency switching applications, reducing energy losses and improving overall system performance.

e) Optoelectronics: InP HEMTs are employed in optoelectronic devices, including photodetectors and optical modulators, for high-speed optical communications. They enable high-speed signal processing and data transmission in fiber optic networks.

VII. CONCLUSION

The analysis of dissimilar High Electron Mobility Transistors (HEMTs) presented in this study sheds light on their material compositions, structural differences, performance metrics, and applications. By examining GaN HEMTs and InP HEMTs, it becomes evident that these advanced semiconductor devices offer distinct advantages in different high-frequency and high-power applications. As HEMT technology continues to evolve, with ongoing advancements in materials, device structures, and fabrication techniques, it holds the potential for further performance improvements and expanded applications. The comparative analysis presented here contributes to the overall understanding of HEMTs and their role in enabling the development of innovative electronic systems that require high-frequency operation, high-power efficiency, and high-speed signal processing.

REFERENCES

[1]. Xiuju Zhou, Qiang Li, Chak Wah Tang and Kei May Lau, “ 30nm inverted In0.53Ga0.47As MOSHEMTS on Si substrate grown by MOCVD with regrown source/drain,” *IEEE Electron Devices Letters*, vol. 33, no. 10, pp. 1384-86, 2010.

[2]. E. Y. Chang, C. I. Kuo, H. T. Hsu, C. Y. Chiang, and Y. Miyamoto, “InAs thin-channel high-electron-mobility transistors with very high current-gain cutoff frequency for emerging submillimeter-wave applications,” *Appl. Phys. Express*, vol. 6, no. 3, pp. 1–3, 2013.

[3]. C. Y. Wu, H. T. Hsu, C. I. Kuo, E. Y. Chang, and Y. L. Chen, “Evaluation of RF and logic performance for 40 nm InAs/InGaAs composite channel HEMTs for high-speed and low-voltage applications,” Proc. 2008 *Asia Pacific Microw. Conf. APMC* 2008, pp. 75–78, 2008.

[4]. P. Ding et al., “Si3N4/Al2O 3 stack layer passivation for InAlAs/InGaAs InP-based HEMTs with good DC and RF performances,” *IEEE J. Electron Devices Soc.*, vol. 6, no. 1, pp. 49–54, 2018.

[5]. B. G. Vasallo et al., “Comparison between the dynamic performance of double- and single-gate AlInAs/InGaAs HEMTs,” *IEEE Trans. Electron Devices*, vol. 54, no. 11, pp. 2815–2822, 2007.

[6]. Y. Q. Wu et al., “Inversion - Type Enhancement - Mode InP MOSFETs With ALD High - K Al2O3 and HfO2 as a gate diellectrics,” *IEEE Electron Device Lett.*, pp. 49–52, 2008.

[7]. A. Kharchenko, “Buffer layers in heterostructures,” *Mod. Electron. Mater.*, vol. 3, no. 4, pp. 154–157, 2017.

[8]. Balandin A et al, “Low flicker - noise GaN/AlGaN heterostructure field-effect transistors for microwave communications”. *IEEE Trans Microw Theory Tech* 47(8):1413–1417, 1999.

[9]. Bhattacharya M, Jogi J, Gupta RS, Gupta M “An accurate charge-control-based approach for noise performance assessment of a symmetric tied-gate InAlAs/InGaAs DG-HEMT. *IEEE Trans Electron Devices* 59:1644–1652, 2012.

[10]. Bollaert S, Cordier Y, Zaknoune M, Happy H, Hoel V, Lepilliet S, The´ron D, Cappy A “The indium content in metamorphic InxAl1-xAs/InxGa1-xAs HEMTs on GaAs substrate: a new structure parameter”. *Solid State Electron* 44:1021–1027, 2000

[11]. Gallium Nitride GaN FETs & HEMTs at www.electronics-notes.com.

[12]. U. K. Mishra, P. Parikh and Yi-Feng Wu, "AlGaN/GaN HEMTs-an overview of device operation and applications," in *Proceedings of the IEEE*, vol. 90, no. 6, pp. 1022-1031, June 2002, doi: 10.1109/JPROC.2002.1021567.

[13]. M. N. A. Aadit, S. G. Kirtania, F. Afrin, Md. K. Alam, and Q. D. M. Khosru, “High Electron Mobility Transistors: Performance Analysis, Research Trend and Applications”, Different Types of Field-Effect Transistors - Theory and Applications. *InTech*, Jun. 07, 2017. doi: 10.5772/67796

[14]. Ai L, Tian F, Xu A, Huang H and Qi M “Effect of InxAl1-xAs graded buffer materials on pseudomorphic InP HEMT”. *Front. Mater.* 9:980077, 2022.

[15]. Kumar, Pawan & Chaudhary, Sumit & Khan, Md & Kumar, Sanjay & Mukherjee, Shaibal. Analytical “Study of ZnO-based HEMT for Power Switching”. 10.21203/rs.3.rs-1140403/v1, 2021.

[16]. Lenka, Trupti & Panda, Ajit & Hills, Palur. “Characteristics Study of Modulation Doped GaAs/InxGa1-xAs/AlxGa1-xAs based Pseudomorphic HEMT”, 2023.

[17]. Bonani F, Guerrieri SD, Ghione G, Pirola M “A TCAD approach to the physics-based modeling of frequency conversion and noise in semiconductor devices under large-signal forced operation. *IEEE Trans Electron Devices* 48(5):966–977, 2001.

[18]. Chang EY, Lin KC, Liu EH, Chang CY, Chen TH, Chen J Submicron T-shaped gate HEMT fabrication using deep-UV lithography. *IEEE Electron Devices Lett* 15(8):277–279, 1994

[19]. Chang C et al Investigation of impact ionization in InAschannel HEMT for high-speed and low-power applications. *IEEE Electron Device Lett* 28(10):856–858, 2007.