Comparative study of GaN HEMT on recent trends and future scope along with its applications

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Abstract.

Gallium nitride has already finds a large scale implementation in the field of optoelectronics and is greatly used in LED lights and it is also well-known material in power applications. Its low operating resistance and high breakdown voltage makes it a great choice to rely on for future implementations of power semiconductors with higher throughput. GaN HEMT (High Electron Mobility Transistor) also finds a large scale implementation in radiofrequency and high power solicitations. It pivots in the field of guided missiles, wireless communication. GaN HEMT are proved to provide higher drain current, cut-off frequency while preserving breakdown Voltages. All of this is possible due to the fact that GaN has higher naturalistic polarization effect and larger band gap energy. Essentially, this study covered a comprehensive review of GaN HEMT as well as its applications in many fields.

Keywords. LED, optoelectronics, RF electronics, EV, HEMT, GaN HEMT.

1. INTRODUCTION

Nowadays GaN is being widely used in various applications, as a basic semiconductor material of devises. The major applications of GaN semiconductor are light-emitting diode (LEDs) and high electron mobility (HEMTs). Due to unique properties like wide-band-gap, high electron mobility, high frequency response, better thermal stability, high switching frequency, GaN is getting a lot of attraction in many sectors like optoelectronics, power electronics, and RF applications. Monolithically manufactured HEMTs have a number of advantages, such as reduced parasitic resistance and capacitance, which increases the power efficiency of the circuit [1], [2]. HEMTs are frequently used in radar, broadcast receivers, and cellular telephones, among other applications. E. J. Lum et.al have pointed out the features of HEMT as well as HBTs. According to his paper it is shown that HEMT performs three times better that MESFET in terms of power efficiency [3]. In LED applications depletion type HEMT is used, but in switching applications and power electronics, normally-off HEMT is needed with high threshold voltage.

This review paper is written following these foot-steps- first we have discussed the background and the structures of depletion type and enhancement type HEMTs. After that various applications of GaN-HEMTs are discussed thoroughly followed by upcoming proposals in different fields. At last future scopes are discussed.

2. BACKGROUND AND STRUCTURE

2.1. Structure of HEMT

The unique property of HEMTs is in producing high carrier mobility 2-D electron gas at equilibrium [4], [5]. A buffer layer is used to overcome the problem of lattice mismatch among two crystals [6], [7]. Throughout the last decade various structural modifications are incorporated to decrease the gate leakage issue and enhance the drain current. Field plates are also used to reduce short-channel-effects (SCEs) for short-gate-length HEMT. In recent times, Air Bridge field plates have also been employed to increase the breakdown voltage of the High electron mobility transistor [3]. The material characteristics of wide band-gap Group III-V materials, especially nitride group semiconductors like GaN, AlN along with SiC, GaAs, are compared with conventional Silicon semiconductor in Table-1.

	Si	GaN	AlN	InN	GaAs	Sic
Band gap	1.12	3.4	6.2	0.9	1.42	3.26
Dielectric Constant	11.8	8.9	8.5	15.3	13.1	NA
Thermal Conductivity	1.5	1.3	NA	NA	0.5	4.9
Break Down Field	0.3	3	11	Low	0.4	3
Electron Mobility	1350	440	300	70-250	8500	720
Lattice Constant	5.43	3.19	3.11	3.53	5.65	3.08

Table 1: HEMT's Material Characteristics [3]

2.2. Structure of GaN HEMT

The two primary forms of GaN HEMT are enhancement type and depletion type. In the case of enhancement type AlGaN/GaN HEMT, we will get the current only if when we give the positive gate voltage. In the case of depletion type AlGaN/GaN HEMT, we will get the current in the channel, even if we do not give the gate voltage.

2.2.1. Structure for Normally-On GaN HEMT and review

Fig-1 depicts a D-mode or depletion mode structure of AlGaN/GaN HEMT. From bottom to top, 1–5 um buffer layer is placed on the top of the silicon substrates followed by unintentionally doped GaN, a AlN spacer layer of 0.7–1.2 nm, and an $Al_xGa_{1-x}N$ barrier layer. $Al_xGa_{1-x}N$ thickness and Al molar fraction (x) are varied between 15 to 30nm and 0.15 to 0.4 respectively. The energy bands of hetero junctions generate a sharp quantum well that is bent downward at which high-intensity electrons are confined at the AlGaN/GaN interface because of the polarization effect with band gap mismatch of AlGaN/GaN [8].

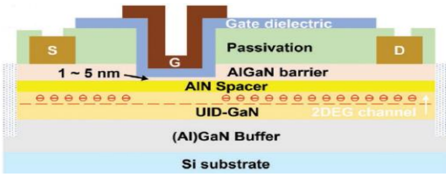
Fig-1: Schematic device structure of normally-on GaN HEMT structure [9].

2.2.2. Structure for Normally-Off GaN HEMT and review

In switching applications and power electronics high positive threshold voltage and normally-off operation is preferred for obvious reason. To achieve normally off operation several structural modifications have been incorporated. Fig-2 shows that under the gate region, an Mg-doped P-type AlGaN is grown. The 2DEG under the Schottky gate is depleted as a result of the increased Fermi level by P-AlGaN, and the conduction band is raised. With a positive gate voltage (Vg > Vth > 0), the device turns on and normally-off operation achieved [10],[11].

Fig-2: p-AlGaN gate enhancement-type HEMT [9].

Two schematics for recessed-gate normally-off HEMTs are shown in Fig-3 and Fig-4. MIS-HEMT construction with a slightly recessed gate and a slender Aluminium Gallium Nitride barrier underneath the gate dielectric [12], [13]. The recessed gate is moved into the AlGaN barrier layer. The threshold voltage rises as the gate electrode gets closer to AlGaN/GaN interface. Normally-off functioning is attained when the depletion zone is created at the AlGaN/GaN interface.



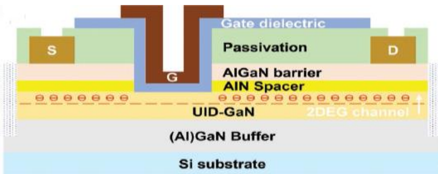


Fig-3: Recessed-gate MIS-HEMT [9]. Fig-4: Recessed-gate MIS-FET [9].

In Fig-5, a limited quantity of fluorine ions enter the channel during implantation and appear as impurities that could cause mobility-impairment. Normally-off operation can be achieved by using ultra-thin AlGaN barrier [14], [15], [9].

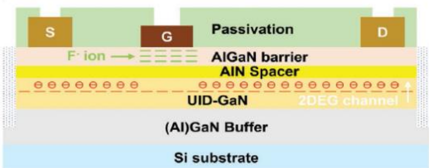


Fig-5: Fluorine gate HEMT [9]. Fig-6: Ultra-thin HEMT [9].

3. GAN HEMT IN OPTOELECTRONICS

The metal organic CVD through selective growth method has already been used to build monolithically integrated AlGaN/GaN to create HEMT and blue LED on sapphire substrates. Few recent literatures are published on GaN HEMT based white LED, where GaN HEMT and LED chip is fabricated in one single chip to light with a wave length of 470 nm N-GaN electrode of current controlled LED and channel region of voltage controlled transistor (HEMT) is connected directly in Fig-7. This is an integrated structure of HEMT-LED [1], [2].

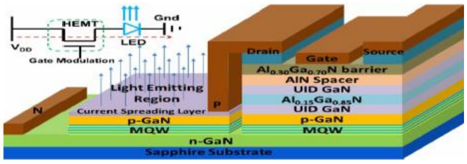


Fig-7: Cross-sectional schematic of HEMT-LED on sapphire substrate [1], [2].

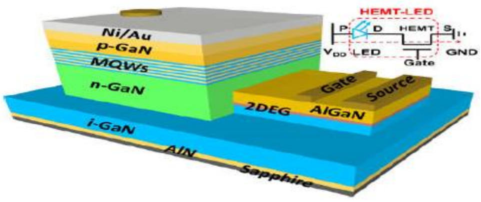


Fig-8: Schematic of the metal-interconnect-free HEMT-LED device using the GaN/AlN buffer [1], [2].

To fully capitalize on the long lifespan of GaN LED chips, the LED system must be enhanced using an on-chip GaN HEMT driver. GaN HEMTs can deliver output current exceeding 1A with great power efficiency. For HEMT-LED monolithic integration technology to be successful, two key elements must be taken into account I) selective epitaxial growth using metal-organic chemical vapour deposition or II) selective epitaxial removal [16], [17].

4. GAN HEMT IN RF AND POWER ELECTRONICS

Applications of power equipment with a rated voltage of 1700 V is often divided into three categories: lower-voltage, mid-voltage, and high-voltage equipment. Applications for mid voltage operate between 10 and 35 kV Fig-9.

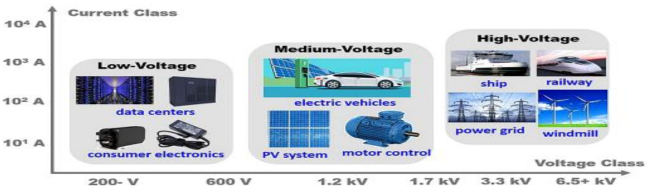


Fig-9: Representative implementation of power electronics applications [18].

The common power device is realized on the basis of lowest on-resistance, high breakdown voltage, as well as modest turn-on or turn-off power losses regardless of voltage or current classes (i.e., switching diminution). SiC is well known material and widely used as substrate materials in HEMT, for high temperature tolerance.

GaN HEMTs are recently used in power electronics applications with a voltage range of 15V to 650V GaN has become great choice of interest compared to silicon and SiC. High power applications need fast switching frequencies, hence GaN HEMTs are being used in wireless charging and rapid adapters. Shrinking of parasitic elements makes it possible to generate high power with high frequency [18].

In Radio-frequency applications AlGaN/GaN or AlGaAs/GaAs HEMTs shows better frequency response compared to conventional semiconductors.

5. GAN HEMT IN VEHICULAR TRANSPORT

Transition to electric vehicles is confronting a number of new obstacles, including the limited number of charging stations and the density of the batteries. For charging up the batteries electric vehicles use several power electronics converters. High cost of these devices, constrained voltage rating, sophisticated gate driver design, and control of thermal resistance become biggest challenges [6], [19], [20].

In the aircraft sector, reliability is more important than price. GaN HEMTs allow for the creation of more compact and lightweight cooling systems by reducing the amount of heat generated by the power electronics. GaN greatly enhances the power density of shipboard converters as well as the ability of switches to function in high temperature [6].

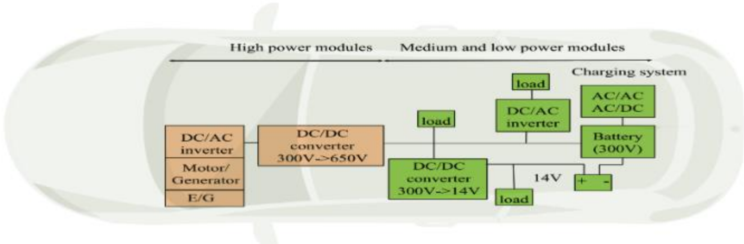


Fig-10: Electric vehicle power electronic components [6].

GaN based devices is anticipated to lower costs and increasing the acceptance of GaN technology and encouraging the creation of more efficient electric vehicles for transport. More electric ships, heavy-duty vehicles, off-road vehicles, and aircraft are just a few examples of what could be in the near future [6].

6. PROPOSAL FOR DEVICE IN DIFFERENT FIELD

In high power applications and millimetre wave applications, GaN HEMTs are a renowned area for research due to its higher breakdown voltage (3.3MV/cm) and high velocity electron ($2.51x10^7$). Better frequency response is achieved by reducing the device gate size as shown in Fig-12. However, much more gate length reduction results in a small channel effect [3].

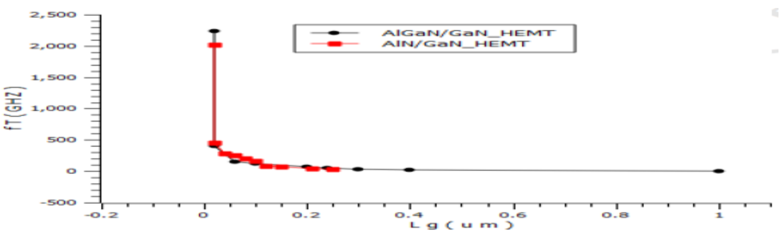


Fig-11: Gate Length V/s Cut-off frequency characteristics of a GaN HEMTs.[3], [20].

The modern wireless power systems uses advanced coil technology and high power amplifiers incorporating GaN HEMTs rather than Si transistors [6].

Gallium Nitride HEMT are particularly applicable for radiofrequency and high power intensive activities because to their wide band gap properties. GaN HEMTs also have significantly greater switching frequency compared to Si-based devices. Therefore, they are suitable for high-speed or wireless charging as well as electrified transportation [18]. Several modifications have done on HEMT structures to enhance the drain current. GaN materials have gained a lot of popularity recently and are useful for improving HEMTs' DC characteristics. GaN is a special kind of material with a 3.4 eV energy gap and a high breakdown voltage of 3MV/cm [3].

7. CONCLUSION

A general review of GaN HEMT along with its applications on different fields is discussed in this paper. Along with that it has also been discussed that GaN based HEMT device are an excellent choice for optoelectronics, radio frequency applications or high power applications, and vehicular transport. But the biggest challenges for GaN HEMT devices is high cost. GaN HEMT devices has limited voltage rating which is another biggest challenge. The complex gate driver design in the production of ICs using GaN are the areas that needs to be improve.

8. FUTURE SCOPE

GaN HEMT has great prospects of further exploration in the near future because of its unique characteristics. GaN HEMT has wide band gap due to high breakdown voltage with high cutoff frequency and has much more wide application in higher frequency domain. Due to high mobility and high carrier concentration, it is much more suitable for switching applications. While we incorporating any other composite materials like InGaN, then it can be also used as a driver circuit for the LED.

9. ACKNOWLEDGMENT

I would like to acknowledge the support shown by Dr. Gourango Sundar Taki and Dr. Satyaranjan Bhattacharyya who guided us during preparation for the manuscript.

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