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A Review of Gallium Nitride (GaN) based devices for High Power and High Frequency Applications

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Abstract

In the past decade with the advent of high speed electronic devices, the global market usage for personal, cellular communication devices and services such as expansion to broadband internet access third, fourth-generation (3G/4G) mobile systems coming closer to reality. In the manufacturing industry, the Radio Frequency (RF) and Microwave power amplifiers are beginning to be the focus of attention. There are numerous high power amplifiers available in the market, giving the industry choices to range from price to performance factors. In this paper, we present the materials properties of Gallium Nitride (GaN) with a comparative analysis to the competing materials used for applications which require higher power and high frequency devices. The reliability issues of Aluminum Gallium Nitride (AlGaN)/GaN based High Electron Mobility Transistors (HEMTs) are the main hurdle for the commercialization of GaN based devices. Due to remarkable potential in other fields, GaN can offer many solutions in the electronic devices. Overall, with help of recent studies, we discuss competitive advantages of GaN based devices and amplifiers for commercial products.

Keywords: Radio Frequency, Microwave, bandwidth, Gallium Nitride, High Electron Mobility Transistors, Aluminium Gallium Nitride

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INTRODUCTION

With recent development in wireless communication, military applications, TV broadcasting, communication satellite the use of microwave transistor plays a very critical role, all these applications require wider bandwidth, high frequencies (X band to Ka band), high power to reduce the antenna size at the user end, wireless internet broadband and its increasing speed or data connections holds the same requirement. To meet these requirements a lot of investment has been done on microwave transistor based Silicon (Si), Silicon Carbide (SiC), Silicon Germanium (SiGe), Gallium Arsenide (GaAs) and Gallium Nitride (GaN). Table 1., shows different parameters of these materials and four figure of merits, Johnson figure of merit (JFoM) (Johnson, 1965), Baliga figure of merit (BFoM) (Baliga, 1982) for low frequencies, Baliga Figure of merit for high frequencies (BHFFoM) (Baliga, 1989) and Keyes figure of merit (KFoM) (Keyes, 1972), all four of these Figure of merits are used in the recent electronics to compare properties of different semiconductors for high power and high frequency applications. The frequency and power limit in figure of merits solely depends on the properties of the material and can be used for comparing the materials for high frequency and power applications.

Table 1. Comparison of materials for High power/frequency applications (Okumura, 2006; Macfarlane, 2014)

Property	Si	GaAs	4H-SiC	GaN	Diamond
E_g (eV)	1.1	1.4	3.3	3.4	5.5
μ_n (cm^2/Vs)	1350	8500	700	700 (Bulk) 2000 (2DEG)	1900
v_{sat} (10^7 cm/s)	1.0	1.0	2.0	2.5	2.7
E_C(MV/cm)	0.3	0.4	3.0	3.3	5.6
JFoM ($E_C . v_{sat} / 2\pi$)	1	7.1	180	760	2540
BFoM ($\varepsilon\mu E_c^3$)	1	15.6	130	650	4110
BHFFoM (μE_c^2)	1	10.8	22.9	77.8	470
KFoM $\kappa(v_{sat}/\varepsilon)^{1/2}$	1	0.45	4.61	1.6	32.1

In contemporary microwave transistors, applications with higher power, frequency requirements, the semiconductors with wide bandgap energy, high electron mobility and high break down voltage are used.

Considering these properties and figure of merits, two semiconductors namely; SiC and GaN are the preferred materials. The JFoM considers two parameter i.e. breakdown voltage of the material and drift velocity of the material. For instance, in case of GaN it is 760 times higher than the Si, and BFoM is actually the measure of permittivity, electron mobility and electric field which is in case of GaN is 650(BFoM) and 77.8(BHFFoM) times higher than Si. KFoM is the measure of thermal constraint to the switching ability of the transistor and in case of GaN it is 1.6 times higher than Si. However diamond is still at early stage of research and requires much more time and investment to compete with GaN devices. Table. 2., shows the GaN material property with the advantage of using GaN based devices which clearly elaborates the application of GaN based devices can meet the requirements of high power applications.

Table 2: Material property & advantage of GaN (Yahaya et al., 2009).

System design outcome	Advantage to GaN Device	GaN Material property
High power capability, reliability, High efficiency, Less cooling requirement, Reduced passive components, Compact system	High breakdown voltage , High current handling, High operating temperature, High switching frequency, Low power losses	High thermal conductivity, High bandgap energy, High breakdown electric field, High saturated drift velocity, High radiation tolerance

Table 3: shows the comparison between the Group-III materials with GaN elaborating GaN the better choice for high power and high frequency application devices.

Table 3: Comparison between Group III materials vs GaN (Yahaya et al., 2009)

Properties	Si	GaAs	SiC	GaN
Suitability for high power	Medium	Low	High	High
Suitability for high frequency	Low	High	Medium	High

Physical Properties of GaN

GaN is a wide bandgap semiconductor with small bond length between the atoms smaller than Si-Si atom bond length, making strong bond energies between the atoms which lead to more stable and inert materials (Okumura, 2006). Figure 1, shows the relationship between bond length and the bandgap energy of various materials used for high power and high frequency applications, where it can be noted that GaN, SiC and Diamond are in separate domain compared to Si and GaAs.

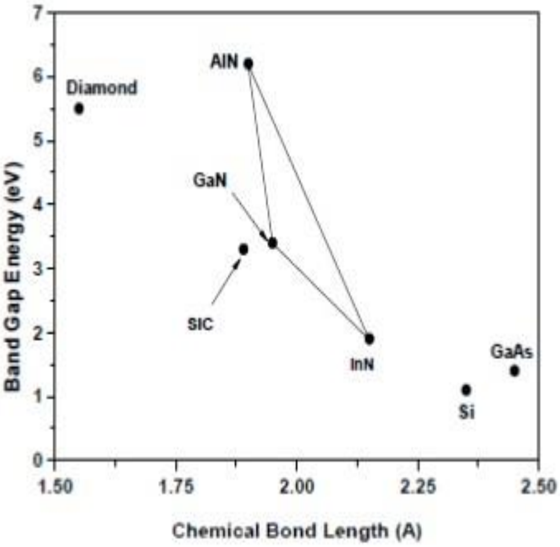


Figure 1: Relationship of bond length band and gap Energy (Okumura, 2006; Macfarlane, 2014)

The crystalline nature of GaN able it to take the form of wurtzite, rock salt or zinc-blende, wurtzite is the most common and easier to grow. The atoms are arranged in alternate pattern (ABAB), two hexagonal layers are closely spaced one of Ga-atom and the other is of N-atom faces both the layers is perpendicular c-axis (Bernardini et al., 1997) as shown in the figure 2.

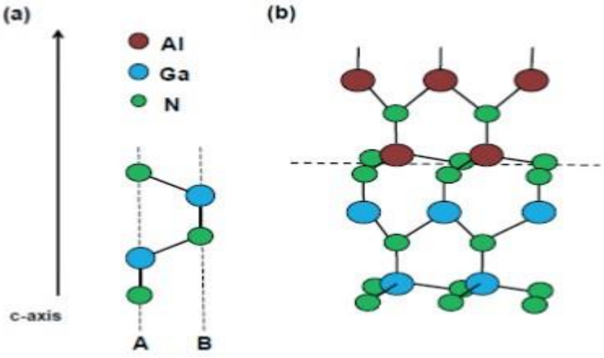


Figure 2: Showing Schematic representation of stacking sequence in wurtzite GaN (Edgar et al., 1999; Ambacher et al., 2000)

GaN Growth and substrate

Group-III nitrides can be grown by metal organic chemical vapour deposition (MOCVD) or molecular beam epitaxy (MBE), for development of GaN the commonly used technique is MOCVD which is carried out at the temperature of about 1000 °C, the reactants for MOCVD are trimethylgallium and ammonia (NH) gas, the growth rate is typically around 1 to 2µm. MBE technique on the other hand compared to MOCVD takes place at lower temperatures (500-900 °C) (Quay, 2008).

SiC

SiC is the most promising substrate it is best lattice matched to GaN, it has the property of high thermal conductivity (4.9W/cm K) which is particularly useful for high power applications, and low thermal expansion coefficient (TEC) mismatch (25%), however lattice mismatch is (3.5%) still it is significant enough to create large defects in GaN layers (108 - 1010 cm), which affects the overall performance of $_3$the device, of the three substrate available SiC is the most expensive still it is regarded as the best choice to grow GaN, most of the GaN RF devices are fabricated on SiC (Quay, 2008)

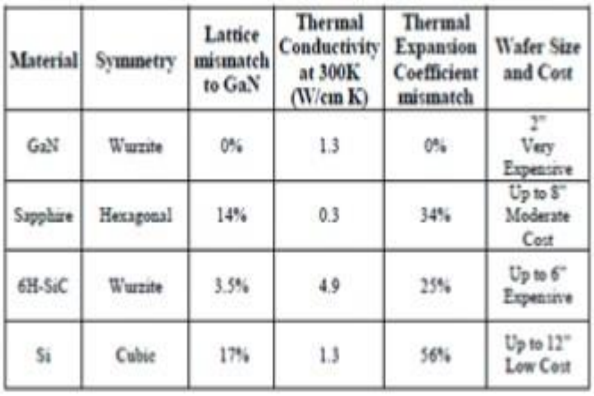
Sapphire

Sapphire is an insulating material having poor thermal conductivity of (0.3 W/cm K) compared to SiC (4.9W/cm K) and high TEC (34%) compared to SiC (25%) lattice mismatch in case of sapphire is (14%) high compared to SiC (3.4%) causing high density dislocations in $_2$GaN layers (1010 cm), despite its drawbacks sapphire is less expensive compared to SiC and is extensively in use over the years for the process and development works.

Silicon (Si)

Silicon has a moderate thermal conductivity of 1.3 W/cm K, with high lattice mismatch (17%) and high thermal expansion coefficient (56%) compared to SiC and sapphire, despite all these drawbacks it is very attractive due low cost and larger diameter wafer available. GaN is grown on Si with 6 inch wafer size$_2$ is commercially available and 8 inch wafer has been demonstrated in the laboratory (Arulkumaran, 2012), which indicates the potential cost saving that could be incurred using Si substrate. Table. 4., shows the comparison of lattice mismatch, thermal conductivity and thermal expansion coefficient mismatch, wafer size and cost of sapphire, SiC and Si with GaN.

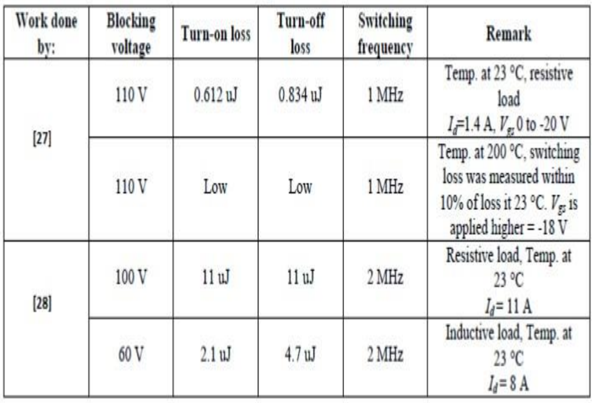
Table 4: Comparison of different substrate material (Edgar et al., 1999; Macfarlane, 2014; Quay, 2008)



Material	Symmetry	Lattice mismatch to GaN	Thermal Conductivity at 300K (W/cm K)	Thermal Expansion Coefficient mismatch	Wafer Size and Cost
GaN	Wurzite	0%	1.3	0%	2" Very Expensive
Sapphire	Hexagonal	14%	0.3	34%	Up to 8" Moderate Cost
6H-SiC	Wurzite	3.5%	4.9	25%	Up to 6" Expensive
Si	Cubic	17%	1.3	56%	Up to 12" Low Cost

Table. 5., shows two studies on the test circuit done on the switching frequency of GaN based devices, the studies proved that if the gate driver circuit is properly designed it can turn on the GaN based switch effectively at its optimum switching frequency. In two different studies it is observed that GaN can operate at 110V blocking voltage and can handle 11A current with the maximum operating frequency of 2 MHz, both the studies carried out at two different temperature levels, the was work done to study the switching behavior of GaN based devices.

Table 5: Switching performance of GaN based devices (Yahaya et al., 2009; Saito et al., 2004; Boutros et al., 2006)



Work done by:	Blocking voltage	Turn-on loss	Turn-off loss	Switching frequency	Remark
[27]	110 V	0.612 uJ	0.834 uJ	1 MHz	Temp. at 23 °C, resistive load I_d=1.4 A, V_{gs} 0 to -20 V
	110 V	Low	Low	1 MHz	Temp. at 200 °C, switching loss was measured within 10% of loss it 23 °C. V_{gs} is applied higher = -18 V
[28]	100 V	11 uJ	11 uJ	2 MHz	Resistive load, Temp. at 23 °C I_d= 11 A
	60 V	2.1 uJ	4.7 uJ	2 MHz	Inductive load, Temp. at 23 °C I_d= 8 A

GaN based HEMTs

High Electron Mobility Transistors (HEMTs) plays a very vital role in high switching applications, nowadays GaN is very frequently utilized to fabricate HEMTs, GaN based HEMTs have high carrier density and high electron mobility that results in large current density, which is an important parameter for high power and high frequency applications (Mishra et al., 2002).

The first demonstration about the AlGaN/GaN HEMTs was given in 1993 (Khan, 1993). After intensive research and development as a consequence the recent development in AlGaN/GaN based HEMTs demonstrated the results at very operating frequency (181GHz) (Higashiwaki et. al 2006), and at 4GHz provided a high power density of 30W/mm (Wu, 2004), with 10W/mm at 40GHz (Palacios, 2005). Figure 3 shows the layer structure of AlGaN/GaN based HEMTs. High Electron mobility Transistors (HEMTs) are basically heterojunction devices of two semiconductors with different band gap energies, In Aluminium Gallium Nitride (AlGaN)/ Gallium Nitride (GaN) based HEMTs a silicon doped AlGaN is grown over GaN, where AlGaN has higher band gap energy than GaN, The silicon donate the electrons in the crystal that are accumulated just below the AlGaN/GaN forming sheet of electrons having 2-dimensional electron gas (2DEG).The electron separated from silicon donor resides in AlGaN where they gain high mobility. For transistor action, the Ohmic contacts for source, gate and drain are produced through photolithography and 2DEG is contacted with source and drain metals whereas the depletion region is controlled with gate contact (Kraus, 2008).

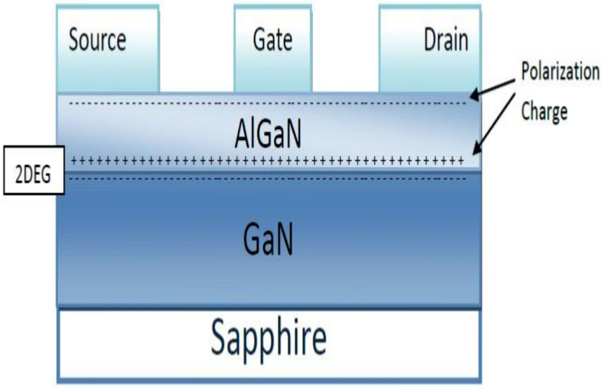


Figure 3: Layer structure for AlGaN/GaN HEMT

Advancement in Breakdown performance of HEMTs

Over a decade or so an extensive research have been done to improve high power AlGaN/GaN based devices, still a lot research needs to be done to find complete engineering solutions, recently the research is being carried out on improving the breakdown fields and breakdown voltages.

The large electric field at the drain edge of the gate is considered to be the limitation in high breakdown voltage of AlGaN/GaN based HEMTs. Somerville and Alamo (Somerville et al., 1996) proposed a solution to this problem, i.e. to employ the vertical structure where drain sits at the bottom of the substrate which will eliminate the problem of large electric field at the drain edge.

Employing vertical structure require much more investment in order to compete with the current processing and designing of lateral AlGaN/GaN devices (Chowdhury, 2012)

Reliability issues in AlGaN/GaN HEMTs

Extensive research is going on identifying the device failure modes, mechanisms, the well-known is gate drain degradation issue, percolative conductive path formation, time dependent trap formation and inverse piezoelectric effect are the physical effects occurs at the origin of device degradation (Zanoni et al., 2013), output current drop, and permanent gate leakage current increase are considered to be the failure modes for AlGaN/GaN HEMTs (Meneghesso et al., 2010), another critical issue concerned to the reliability of GaN based HEMTs is trapping of charge and the identification of traps (Karumuri et al., 2013).

GaN based HEMTs Low Noise Amplifiers(LNA)

GaN based HEMTs devices are usually intended as high switching devices, it has a significant potential

In other fields for example in integrated circuits including the transmitter and receiver end, GaN based LNA provide high linearity and robustness at the input power of 40dBm without affecting gain too much (Colangeli et al., 2013), the capacitor less gate driver circuit has also been proposed for GaN based high power application devices to improve the efficiency, results demonstrated high efficiency of capacitor less driver circuit compared to the capacitor type gate driver circuit (Umegami et al., 2013).

GaN the technology for the Future

The reliability consistency of GaN with the system requirement is the only obstacle in the commercialization of GaN, extensive research is in progress to sort out reliability issues, device failure modes of GaN based high power and high frequency devices. GaN based RF applications has made a significant progress in technology process, growth of material and at Monolithic Microwave Integrated Circuits (MMIC) in past decade or so.

Power Amplifiers and Monolithic Microwave Integrated Circuits (MMICs) in the near future will be based on GaN technology, AlGaN/GaN based HEMTs with high power density and high power added efficiency (PAE) for wide band frequencies is under research.

Moreover, AlGaN/GaN based HEMTs are considered to be the better choice for designing Low Noise Amplifiers (LNAs) (Colangeli et al., 2013) because it can offer low noise performance with high breakdown voltages, AlGaN/GaN is considered to provide optimized solutions to the high power and high frequency applications.

REFERENCES

0 Ambacher O, Foutz B, Smart J, Shealy JR, Weimann NG, Chu K, Murphy M., Sierakowski KJ, Scha WJ and Eastman LF. (2000). Two-dimensional electron gases induced by spontaneous and piezoelectric polarization charges undoped and doped AlGaN/GaN hetereostructures. *Journal of Applied Physics*. 87: 334 -344.

0 Arulkumaran S, Ng GI, Vicknesh S, Wang H Ang KS, Kumar C M M, Ranjan K and Lo G-Q. (1982). Tripathy S, Boon CC and Lim WM. GaN-on-Silicon integration technology in 2012 IEEE International Symposium on Radio-Frequency Integration Technology (RFIT). 159-161.

0 Baliga BJ. Semiconductors for high-voltage, vertical channel field-effect transistors. *Journal of Applied Physics*. 53: 1759-1764.

0 Baliga BJ. (1989). Power semiconductor device figure of merit for high-frequency applications. *IEEE Electron Device Letters*. 10(10):455-457.

0 Bernardini F, Fiorentini V and Vanderbilt D. (1997). Spontaneous polarization and piezoelectric constants of III-V nitrides. *Physical Review B.* 56: R10024-R1002.

0 Boutros S, Chandrasekaran S, Luo WB and Mehrotra V. GaN Switching Devices for High-Frequency, KW PowerConversion. IEEE International Symposium on Power Semiconductor Devices. 1-4, June 2006.

0 Chowdhury S, Wong MH, Swenson BL and Mishra UK. (2012). CAVET on bulk GaN substrates achieved with MBE-regrown AlGaN/GaN layers to suppress dispersion. *IEEE Electron Device Letters.* 33: 41-43.

0 Colonel, Bentini A, Ciccognani W, Limiti E and Nann A. (2013) GaN Based Robust Low-Noise Amplifiers. *Electron Devices, IEEE Transactions.* 60(10):3238-3248.

0 Edgar JH, Strite S, Akasaki I, Amano H and Wetzel C. Gallium Nitride and Related Semiconductors. INSPEC, 1999.

0 Higashiwaki M, Mimura T and Matsui T. (2006). 30-nm-Gate AlGaN/GaN Heterostructure Field-Effect Transistors with a Current-Gain Cutoff Frequency of 181 GHz. *Jpn J Appl Phys.* 45(42-45): L1111-L1113.

0 Johnson EO. (1965). Physical limitation on frequency and power parameters of transistors. *RCA Rev.* 163–176.

0 Karumuri and Rahman N. Gate Leakage Mechanisms in AlGaN/GaN and AlInN/GaN HEMTs: Comparison and Modeling" from Turuvekere et al., from IIT Madras and Tata Institute of Fundamental Research, Mumbai, India, 2013.

0 Keyes RW. (1972). Figure of merit for semiconductors for high speed switches. *IEEE Proceedings*. 10: 225.

0 Khan MA. High Electron Mobility Transistor Based on a GaN-AlxGa1-xN Heterojunction. *Applied Physics Letters*. 63(9): 1214-1215.

0 Kraus T. AlGaN/GaN HEMTs Monolithic Microwave Intergrated Circuits; Modeling, Design, Fabrication and Characterization, Master's Thesis, 2008.

0 James MD. Design and fabrication of AlGaN/GaN HEMTs with high breakdown voltages. PhD thesis, School of Engineering, University of Glasgow, 2014.

0 Meneghesso G, Meneghini M, Tazzoli A, Ronchi N, Stocco A, Chini A and Zanoni E. (2010). Reliability issues of gallium nitride high electron mobilitytransistor. *Int. J. Microw. Wireless Technology*. 2: 39 -50.

0 Mishra U, Shen L, Kazior T and Wu Y. (2008). GaN-Based RF Power Devices and Amplifiers. *IEEE Proceedings*. 960(2): 287-305.

0 Mishra UK, Parikh P and Wu YF. AlGaN/GaN HEMTs-An overview of device operations and applications. *Proceedings of the IEEE*. 90(6):1022–1031.

0 Okumura H. (2006). Present status and future prospect of wide gap semiconductor high power devices. *Japanese Journal of Applied Physics*. 45(10): 7565-7586.

0 Palacios T. (2005). High-power AlGaN/GaN HEMTs for Ka-band applications. 26(11): 781-783.

0 Saito W, Kuraguchi M, Takada Y, Tsuda K, Omuraand L and Ogura T. (2004). High breakdown Voltage undopedAlGaN/GaN power HEMT on sapphire substrate and its Demonstration for DC-DC converter application. *IEEE Transactions on Electron Devices*. 51(11):1913-1917.

0 Somerville MH and Del- Alamo JA. A model for tunneling-limited breakdown in high-power HEMTs," in International Electron Devices Meeting, 1996. 35-38, Dec. 1996.

0 Umegami H and Yamamoto M. (2013). Capacitor-Less Gate Drive Circuit Capable of High-Efficiency Operation for Non-Insulating-Gate GaN FETs. Electron Devices. *IEEE Transactions.* 60(10): 3249 – 3255.

0 Wu YF. (2004). Electron Device Letters. *IEEE*. 25(3):117-119.

0 Zaihar YN, Raethar MBK and Awan M. (2009). Review on Gallium Nitride HEMT Device Technology for High Frequency Converter Applications. *Journal of Power Electronics.* 9:109.

0 Zanoni E, Meneghini M, Chini A, Marcon D, Meneghesso G. (2013). AlGaN/GaN-based HEMTs failure physics and reliability: Mechanisms affecting gate edge and Schottky junction. *IEEE Trans. Electron Dev*. 60: 3119-3131.