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Review on Gallium Nitride HEMT Device Technology for High Frequency Converter Applications

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ABSTRACT

This paper presents a review of an improved high power-high frequency III-V wide bandgap (WBG) semiconductor device, Gallium Nitride (GaN). The device offers better efficiency and thermal management with higher switching frequency. By having higher blocking voltage, GaN can be used for high voltage applications. In addition, the weight and size of passive components on the printed circuit board can be reduced substantially when operating at high frequency. With proper management of thermal and gate drive design, the GaN power converter is expected to generate higher power density with lower stress compared to its counterparts, Silicon (Si) devices. The main contribution of this work is to provide additional information to young researchers in exploring new approaches based on the device's capability and characteristics in applications using the GaN power converter design.

Keywords: Gallium nitride device, High frequency, Power converter

1. Introduction

Gallium Nitride (GaN) high-electron mobility transistor (HEMT) is one of the wide bandgap (WBG) semiconductor group III-V devices, besides Silicon Carbide (SiC) and diamond. These devices are known to have large energy bandgap ranging from 2.3 eV to 5.6 eV while Silicon (Si) devices normally have smaller energy around 1.12 eV. This difference in energy bandgap makes group III-V devices superior in high speed operations and thermal handling capability. The emergence of the WBG devices results in substantial improvement of power electronic converter systems in terms of higher blocking voltages, efficiency and reliability.

The first study of GaN devices was initiated in 1970s by Ponkove, Akasaki and many others [1]. Currently, GaN has been widely used in optoelectronics and microwave applications in the form of nitride-based light emitting diodes (LEDs) especially in mobile phones. The latest GaN device was tested for radio frequency (RF) operation at frequencies up to 110 GHz [2]. In transistor switch operation, GaN has been demonstrated with blocking voltages of 600 V [3] which is suitable for high voltage switching operation. The maximum current handling capability is 30 A when developed on SiC substrates [4].

GaN is preferred due to its ability to improve utility applications compared to other non III-V group devices such as silicon-based transistors such as power MOSFETs. With regards to power supply development, a high power MOSFET switch can operate at a maximum operating frequency of 500 kHz with current handling capability of

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Table 1[5] Advantages and Material's Property of GaN Device

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

100 A and 2000 VA power rating. However, GaN is expected to perform far better than Si based devices. Table 1 shows a summary of the GaN device's characteristics, properties and advantages in high power applications.

As indicated in Table 1, GaN shows superiority in high power and high frequency applications. However, the fabrication processes in developing a bulk of good GaN devices presents great challenges to researches around the world in ensuring the suitability for the designed applications. The details of the fabrication technology are elaborated in the next section.

2. GaN Device Fabrication Technology

The first preliminary fabrication work on GaN devices was reported by S. Yoshida et al in 1999 [6]. At that time, the device was not yet available for commercialization because of the difficulties in Wurtzite-crystal growth. There was no bulk of GaN substrates available. In 2001, Ric Borges et al [7] revealed that GaN was difficult to grow on either sapphire or SiC. The GaN layer was then instead grown on Si because sapphire and SiC substrate materials were expensive which made it unable for commercialization. The fabrication of GaN was through Metal-Organic Chemical Vapor Deposition (MOCVD).

Then RF Micro Devices managed to fabricate a GaN layer on sapphire and SiC substrates using a patented single-temperature, low pressure Organometallic Vapor Phase Epitaxy (OMVPE) growth technique in 2001 [8]. From this work, it was found that the total power for GaN on sapphire and on SiC was 22.6 W and 108 W respectively. GaN devices grown on sapphire offered five times better performance over GaN grown on Si due to higher power gain, lower lattice mismatch and superior semi-insulating properties [9].

In 2004, a 600 V/2.5 a GaN device rating was successfully developed [10]. The GaN epi-layers were grown on semi-insulating SiC substrate using the MOCVD technique. The SiC substrate was chosen due to its performance in high thermal conductivity and high blocking voltage.

In other studies, different configuration techniques have been attempted in the fabrication of GaN. Among them was the development of AlGaN/GaN HEMT. Here the Si-doped AlGaN is grown on top of GaN [11], as shown in Fig. 1. Since AlGaN has higher energy bandgap that GaN, Si, impurities will donate electrons to the crystal which will then accumulate in the lowest potential region beneath the AlGaN/GaN interface.

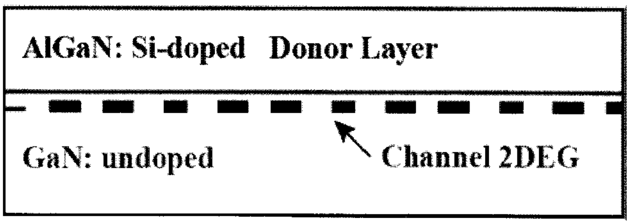

Fig. 1 Modulation-doped heterostructure of AlGaN/GaN [7]

The sheet of electrons results in a 2DEG (2D electron gas). The electrons will experience higher mobility since they are separated from the ionized Si donor in the AlGaN. The electron mobility velocity of the 2DEG is about 1500 cm^2/Vs [12, 13] which is significantly better than SiC. This AlGaN/GaN modulation-doped heterostructure configuration is beneficial in exploring the power handling capabilities and high frequency potential where higher current handling possibility is compensated by higher channel charge in the heterostructure region.

The development of AlGaN/GaN HEMT on sapphire substrate with Field Plate (FP) and undoped AlGaN/GaN layer had also been attempted using MOCVD technology [14]. The device was successfully tested under high voltage of 300 V and high switching operation. The undoped AlGaN layer was determined to reduce gate leakage current of the GaN device and this growth of sapphire substrate realized ultralow on-state resistance.

Due to higher electron mobility, high saturation velocity, high sheet carrier concentrations at heterojunction interfaces, high breakdown fields, low thermal impedance (when grown on SiC substrates) and low on-state resistance, AlGaN/GaN HEMT significantly offers a better and efficient device close to that of SiC [8], [15-17].

3. GaN Material's Properties and Comparison with Other Devices

From Table 1, GaN takes control in the bandgap energy, high breakdown electric field, high thermal conductivity, high saturated drift velocity and high radiation tolerance. In this section, GaN material's properties are compared with other Si-based devices and it is found that GaN serves better in power electronic applications. The comparison between GaN and other semiconductor devices is shown in Table 2.

Table 2 Silicon based vs. Group III-V Materials

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

Table 2 indicates that GaN devices are superior in all aspects of the said properties. In relation to the suitability for high power and high frequency applications, GaN is also capable in thermal conductivity and higher temperature handling. The physical characteristics of an expected WBG device should manage to overcome the following limitations in Si.

3.1 Voltage blocking capability

Si device has a narrow energy bandgap, around E_g = 1.12 eV which leads to low intrinsic breakdown of the electric field. The voltage blocking of Si is only less than 10 kV. However, high voltage operation using Si requires a series of staking layers and this is costly. In addition, Si has large on-resistance which means higher power losses, resulting in efficiency limitations. Thus, this has an adverse effect on current density and switching speed.

3.2 Switching frequency

Si has a limited switching frequency due to heat dissipation resulting from switching losses in the device. Normally a Si-based transistor such as a power MOSFET experiences noise and stress beyond 500 kHz [14]. The converters with higher switching frequency requires less filtering, small passive components and exact control system. These factors indirectly influence the switching speed of the device.

3.3 Thermal conductivity

Due to low thermal conductivity in Si, it can only limit its temperature operation up to 150 °C. As temperature increases, heatsink is required as the cooling device apart from natural air, forced air and water cooled heatsinks. Normally, the power rating of a converter determines the type of heatsink to be used.

3.4 Temperature limitation

Power losses in Si are associated with the switching operation of the device. For high voltage and current applications, Si-based devices generate higher switching losses. As a result, WBG devices are required. Table 3 summarizes the related physical properties for the Si device and its relationship with respect to the characteristics of the WBG devices.

From Table 3, GaN shows remarkable ability in high breakdown voltage where it can operate in high voltage applications [5], [18]. It also presents the highest saturated electron drift velocity and has advantages in higher switching operation. Hence the size of passive components can be reduced. Consequently, the total volume of the converter can be packed into a smaller size with higher power density.

Table 3 Comparison between GaN and Other Semiconductor Devices

Property	**Si**	**GaAs**	**4H-SiC**	**GaN**	**Remark**
Bandgap E_g (eV)	1.12	1.43	3.26	3.45	High bandgap energy results in high breakdown voltage hence large power capacity
Electric breakdown field E_c (kV/cm)	300	455	2200	2000	High breakdown field results in high current density hence high reliability and efficiency Having thinner drift layer that reduces on-state resistance
Thermal conductivity λ (W/cmK)	1.5	0.46	4.9	1.3	High thermal conductivity results in high operational temperature hence less cooling required and efficient heat removal. Having low intrinsic carrier concentration without thermal runway
Saturated electron drift velocity V_{sat} (x 10^7 cm/s)	1	1	2	2.2	High saturated e-drift velocity results in high switching frequency & high current handling hence reduced volume of passive components

However, GaN has some drawbacks in electric breakdown field and thermal conductivity where it could not perform as well as SiC semiconductor devices. Growing GaN on SiC wafers increases overall thermal conductivity but it does not reach the performance of SiC [19]. These are the tradeoffs where GaN requires circuit design optimization in the application of high power and high frequency converter systems.

4. Issues in WBG Semiconductor Devices

Despite having superiority in high frequency switching performance, the WBG semiconductor devices such as GaN and SiC are not easy to manufacture. Some of the problems encountered are low quality and low defect materials, poor doping control and ohmic contact in heterostructure layer [7].

The application of the switching performance testing has only been done with low current handling capability circuit. Hence large parasitic ringing in the circuit hinders the extraction of switching losses [20]. Other important issues are listed below:

a) Designing a high power converter that contains fast switching devices also requires the reduction of manufacturing costs.
b) As frequency increases, the size of active and passive components reduces. The new design of these components will ensure a compact size and reliability of converters.
c) Correct packaging and thermal management will be required to improve switching speed of the device as

Table 4 Switching Performance of GaN Devices

Work done by:	Blocking voltage	Turn-on loss	Turn-off loss	Switching frequency	Remark
[10]	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
[20]	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

well as maintain operation at high voltage and high temperature levels.

d) Cooling of the printed board requires reduction of primary energy saving (PES).

e) Maximum efficiency of the converter is required in order to save energy. At the same time, cooling requirements are monitored to improve the device's performance.

f) Feedback control systems and gate drive techniques are necessary in order to effectively turn on GaN switch at maximum switching frequency. In this case, new hardware and control strategies are required.

5. High Frequency Demonstration Using GaN Device

There were lots of studies about the switching performance of the GaN transistor switch [4],[10],[14]. Most of them involved the standard inductive and resistive chopper circuit to test the fabricated GaN switch where the device was tested on the switching losses at a very high frequency pulse. However, the turn-on process is found to be difficult. This is due to the exact gate drive circuit which needs to be correctly designed in order to turn on the GaN switch effectively at its maximum switching frequency.

Fig. 2 shows the typical test circuit for the switching performance of the device. Under testing, the GaN HEMT is configured for maximum switching frequency by the gate drive circuit. The device is tested in high voltage and frequency operations. From the experiments, GaN showed an improvement in speeds greater than 2 MHz [4], [21].

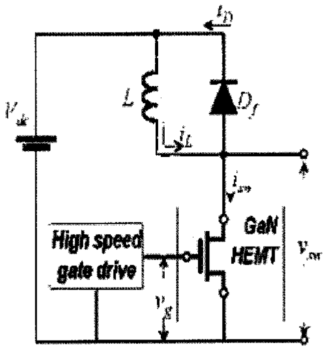

Fig. 2 Test circuit [20]

In addition, the test circuit can be applied to investigate and observe the maximum switching limit that GaN can perform until failure. The result is then compared with the Si device when employed as a switch. Table 4 shows some of the work done in testing the GaN switching performance.

In two different studies as indicated in Table 4, the GaN device can withstand an operating frequency of 2 MHz in two temperature levels. The blocking voltage is around 110 V with current handling capability of 11 A..

This shows that GaN can handle higher voltage and current with the ability to operate in high switching frequency.

6. Conclusion

GaN is expected to offer better efficiency and thermal management with higher switching frequency. Additionally, by having higher blocking voltage, GaN can be used in high voltage applications. In high switching frequency operation, the weight and size of the passive components on the printed circuit board can be reduced. With proper thermal management and gate drive design, the GaN power converter is expected to generate higher power density. Thus, this presents a better choice switching device for future high power converter operations.

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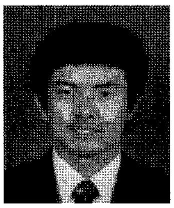

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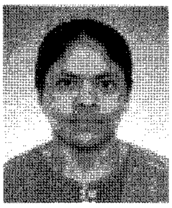

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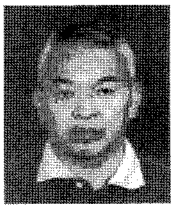

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