ENHANCED CHARACTERISTICS FEATURES OF GALLIUM NITRIDE HIGH ELECTRON MOBILITY TRANSISTOR FOR POWER DEVICES APPLICATIONS

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Abstract

Gallium Nitride (GaN) is a versatile material due to its direct and wide band gap, robust thermal stability, high electric breakdown field, high saturation velocity, high electron mobility and lower capacitance. But for power device applications, the choice of substrate, which match, the lattice as well physical properties have been a great challenge in fabrication process of High Electron Mobility Transistor (HEMT). The materials Silicon, Sapphire, Silicon Carbide and Aluminum Nitride has been tried as substrate in heterojunction development, and a significant improvement in characteristics features of GaN HEMT for high frequency power applications have been reported. The present paper critically analyzes, the development of HEMT in relation to substrate choice and enhanced characteristics features.

Keywords: Gallium Nitride, Band gap, Silicon, Mobility, Characteristics.

1. Introduction

Already, the large bandgap Gallium Nitride semi-conductor & it's alloy Aluminum Gallium Nitride are surfacing as notably viable materials for a variety of applications [1]. Because of its reliable thermal stability & electronic characteristics, it becomes a perfect choice for operation in a severe & intense environment [2] . GaN has showed the possibility for achieving the conditions in switching devices to operate at high-temperature and high-power. Being a wide bandgap material, it shows high electric breakdown field, much greater as compared to Silicon. The high electric breakdown field allows gallium nitride to be used in devices which are operated at higher bias voltages., therefore gallium nitride becomes appropriate material in manufacturing devices which operate at high-voltage. Gallium nitride is regarded as an outstanding material for high-frequency and high-power applications which is also used in the field of optoelectronics. These devices show significant enhancements in characteristics which can also operate under high temperature conditions ranging between 300°C and 700°C whereas silicon power devices cannot operate in these conditions [3]. Higher breakdown field of GaN acknowledge development of devices with narrower drift regions, resulting reduced specific on state resistance. Overall, GaN leads to a device with lesser on-resistance and switching losses as compared to a Silicon device under similar operating conditions[4]. For a given semiconductor material, a device's capacity for faster switching is dependent on its carrier drift velocity which is about two times greater for GaN when compared to Silicon & also greater when compared to Silicon carbide. By implementing appropriate thermal management, this quality is feasible in high-frequency switching applications. Greater drift velocity allows quicker charge withdrawal from the depletion region at the time of fast switching & consequently, minimize the reverse recovery time. Radiation hardness may be used in satellite and space electronic systems in which exposure to intense ionizing cosmic radiation becomes a big issue [5]. The key material parameters of some important materials used in high frequency applications are presented in Table-1.

Table 1. Comparison of various material parameters of the important materials which are used in high frequency devices [6].

Material	**Energy band gap (electron-volt)**	**Breakdown Field (MV/cm)**	**Thermal conductance (W/cm.K)**	**Mobility ($cm^2/V.s$)**	**Electron saturation velocity ($10^7 cm/s$)**
Silicon	1.10	0.3	1.5	1300	1.0
Gallium arsenide	1.40	0.4	0.5	6000	1.3
Silicon carbide	3.20	3.0	4.9	600	2.0
Gallium nitride	3.40	3.0	1.5	1500	2.7

Gallium nitride semiconductor devices show low power loss in electrical energy conversion due to its lower on state resistance and capacitance. Therefore, GaN devices are ideal for high-frequency, high-efficiency, and high power density power converters. Gallium nitride devices properties are also used in power electronics systems like High-electron-mobility transistors (HEMTs) [7].

2. Substrate Choice for AlGaN/GaN HEMTs

Lattice mismatch, thermal conductivity, coefficient of thermal expansion (CTE), and isolation are some of the substrate materials' most crucial physical characteristics that should be taken into account for III-N devices. Table 2 provides a summary of the key physical characteristics of the substrate materials that are being considered for III-N devices.

Table 2 Basic Properties of Semiconductor Materials used as Substrate

Property	**Silicon**	**Sapphire**	**Silicon Carbide(SiC)**	**Gallium Nitride (GaN)**	**AIN**
Crystal Structure	FCC	HCP	HCP	HCP	HCP
Lattice constant (A°)	5.43	2.747	3.08	3.189	3.112

Thermal Conductivity(W cm^{-1}K^{-1})	1.5	0.5	4.9	1.3	2
Lattice Mismatch to GaN(%)	16.9	13	3.4	0	2.4
Coefficient of Thermal Expansion(10^{6} K^{-1})	3.59	7.5	4.2	5.9	4.2
Isolation(Ohm cm)	$(1 – 3) x10^{4}$	_-	$\geq 10^{11}$	$\geq 10^{9}$	$\geq 10^{12}$
Thermal Mismatch (%)	55	-23	30	0	34

It may be seen that, in case of SiC, the properties; thermal conductivity, lattice mismatch and isolation are favourable with GaN and so SiC is taken as the suitable substrate material for fabrication of power devices. [8, 9, 10, 11]. Due to their great heat conductivity, GaN-on-SiC devices also offer the best electrical characteristics and device longevity. GaN on SiC wafers are available in sizes up to 4 to 6 inches with increasing quality [12,13,14]. On semi-insulating SiC materials, the majority of the excellent electronic device performances have been reported [15].

SiC provides a number of advantages, but there are several growth issues that still need to be fixed. For instance, GaN cannot be grown directly on SiC due to its low wetting capacity. Three-dimensional islands will appear at the start of growing, which will lower the GaN film's quality. AlN was proposed as a buffer layer by L. Lie et al. to circumvent this problem. Because the AlN effectively moistens the SiC, this occurs. AlN, which has a lattice constant between GaN and SiC, has also been shown to significantly improve the quality of the GaN layer produced on SiC. The AlN buffer also significantly reduced the risk of TEC mismatch-induced GaN cracking on SiC. The 3.2 percent TEC mismatch between GaN and SiC (Table 4) will cause the GaN layer produced on SiC to break if the tensile stress is not appropriately controlled. In addition to AlN, other buffer materials, such as AlGaN, can be used. Additionally, as SiC is a somewhat pricey substrate on the market, less expensive alternatives are preferred.

Sapphire is another material that shows promise because inexpensive substrates with a diameter of 2-4 inches are readily available. However, 6 and 8 inch substrates have recently been manufactured with success [16, 17]. Despite its poor thermal conductivity and lattice mismatch, GaN-based light emitting diodes and other electronic devices are frequently made with it (LEDs). High pulsed output powers and very outstanding power densities of >12Wmm-1 have been seen in it [18, 19].

Silicon is the most significant semiconductor and substrate material due to its economic significance and extensive use, making its use as a substrate appealing, mostly for reasons of cost effectiveness. Large silicon wafer widths (ranging from 8 inches to 12 inches) are available, and a sizable infrastructure (foundries) based on silicon already exists for the production of silicon wafers [20].

However, the use of silicon substrates presents some difficulties due to the different thermal expansion coefficients between the substrate & the gallium nitride semi-conductor, especially in high-power operation. The silicon substrate also has lattice mismatch with gallium nitride which affects its material quality, device reliability and also increases crystal defects.[21,22].
High quality GaN structure growth on Si is more challenging to achieve because Si and GaN have different lattice constants and thermal expansion coefficients. In general, there are numerous flaws, and the cooling process can cause the gallium nitride layer to crack. These problems can be solved by building buffer layer to produce GaN epitaxial layers on silicon substrates having excellent stability, better quality, and without any fractures (figure 1). There are two conceivable designs for the buffer layer: Aluminum gallium nitride/Gallium Nitride superlattice growth through the step gradient Aluminum gallium nitride layer, & Aluminum gallium nitride/gallium nitride superlattice. In order to address these issues, it is possible to build an epitaxial layer of GaN on silicon substrates with better quality and uniformity, without any fractures by growing buffer layer (figure 1). Aluminum Nitride/Gallium Nitride super-lattice build up by the step gradient Aluminum Gallium Nitride layer and Aluminum Gallium Nitride /Gallium Nitride superlattice are two possible designs for the buffer layer. The significant difference in thermal expansion coefficient between GaN and Si is mitigated by a multilayer buffer arrangement. It helps avoid cracking and produces a flat wafer by introducing compressive strain during the growing phase to balance the tensile strain introduced during cooling. Furthermore, the quality and resistivity of GaN-based templates have an impact on the breakdown voltage in GaN HEMTs. Higher resistivity buffer layer is also required for an efficient GaN channel in order to stop DC leakage current and AC coupling. The resistance of the underlying buffer layer will affect the characteristics of GaN high-frequency power amplifiers, mostly because of the signal coupling effect. But other groups have adopted various techniques to increase the resistivity of the buffer layer, by doping p-type impurity in order to strengthen the buffer structure of Gallium Nitride. Utilizing carbon dopant, which has a more desirable effect in the buffer layer, is another approach. The storage effect of the carbon-doped technique is weak in comparison to the magnesium example. The breakdown voltage and carrier concentrations are regulated by various epitaxial conditions in accordance with the doped buffer layer. On the other hand, polarisation charges in nitride-based materials are crucial because the top barrier layer contains Aluminum gallium nitride or Indium aluminum nitride, which causes 2-dimensional electron gas in High elctron mobility transistor. The lattice mismatch of GaN would limit the Al content and thickness even when the thin AlGaN layer is developed on the GaN channel layer. By varying the barrier thickness and the composition of the aluminum, the interface charge may be changed. Because InAlN has a thicker critical thickness than AlGaN, it could reduce epitaxial flaws. It demonstrates that a layer of InAlN with good lattice matching, has enhanced spontaneous polarisation to provide an increased channel charge density. [23].

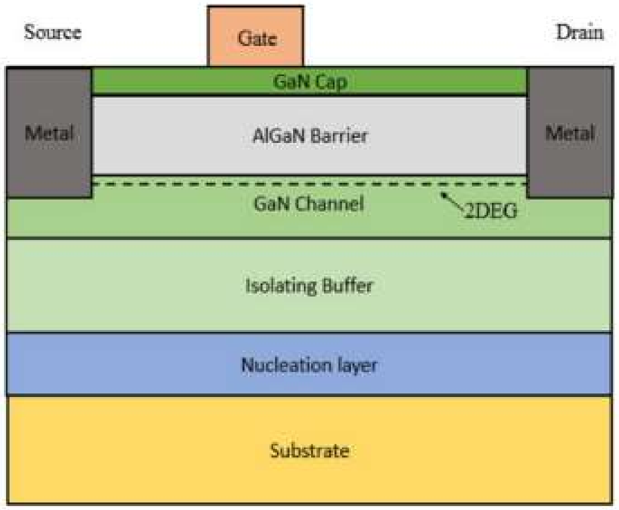

Figure. 1. Epitaxial layer structure of GaN High Electron Mobility Transistor on Si substrate [23].

3. Current–Voltage Characteristics of AlGaN/GaN HEMT using Silicon as Substrate

3.1 Static Current-Voltage Characteristics

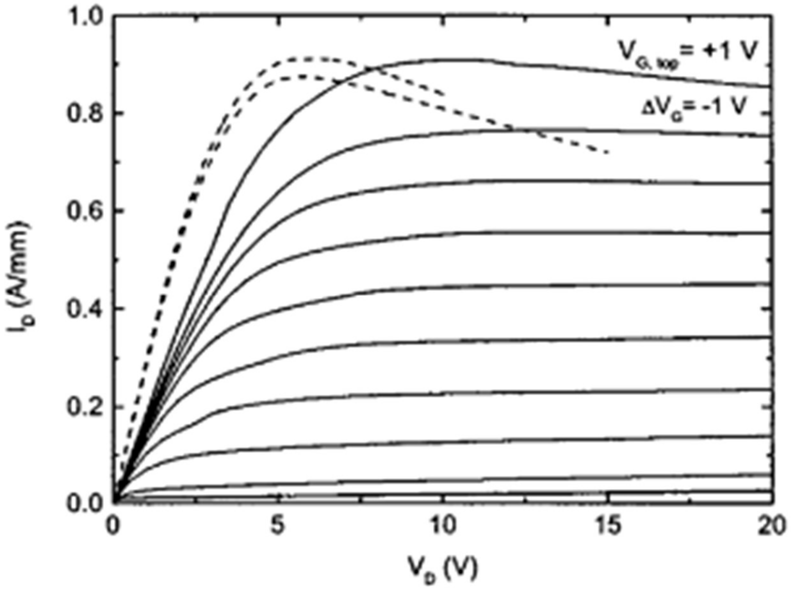

Figure. 2 Static Current–Voltage characteristics of AlGaN/GaN HEMT using substrate silicon substrate (full lines) and sapphire (dotted lines) [24]

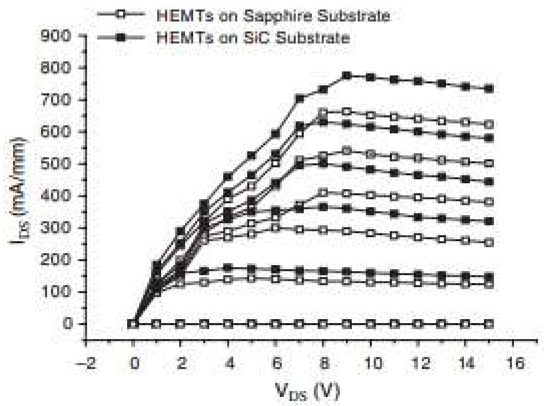

Figure. 3. The Current–Voltage characteristics of the AlGaN/ GaN HEMTs on sapphire and SiC substrates [25]

Fig. 2 displays typical static output characteristics for devices with 0.3 m gate length. The gate voltage varied from +1 V to -10 V at interval of 1V. The drain current is measured by changing drain voltage up to 20V. The output conductance is low, and the thermal effects are barely noticeable. At 1 V on the gate, a drain saturation current of 0.91 A/mm is obtained. This is greater than what has previously been documented for AlGaN/GaN HEMTs on Si [4] and is on par with values for high-performance microwave power HEMTs on SiC substrates (Figure 3). In compared to comparable devices grown on sapphire, HEMTs on Si substrates can withstand a substantially higher dc power. For devices on Si, the drain current reduces just marginally (V_G=+1V) or remains nearly constant (V≤ 0V) with increasing drain voltage (Fig. 2). The increased thermal conductivity of Si compared to sapphire results in an improvement in heat dissipation. As a result, the impacts of channel heating are greatly diminished, keeping performance almost intact [26].

3.2 Transfer Characteristics and Transconductance

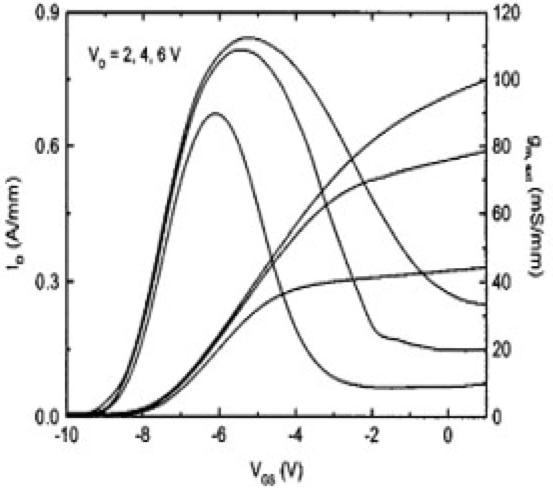

Figure 4. Transfer characteristics and transconductance of AlGaN/GaN HEMT. [27]

The transfer characteristics of Aluminum gallium nitride/gallium nitride High electron mobility transistor fabricated using Substrate Silicon are presented in Figure 4. At V_G=-5V, 122 mS/mm of peak extrinsic transconductance was recorded. This is just marginally less than what was reported for high-performance GaN-based HEMTs on SiC for microwave power (Figure 5). More improvement could be made, though, by increasing the High electron mobility transistor dimensions, mainly the gate length & the gate drain spacing. High electron mobility transistor on silicon has threshold voltage equal to - 9 Volt, as opposed to the - 6 Volt observed in sapphire substrate. A little bit above 40 V is discovered to be the breakdown voltage at pinch off [27].

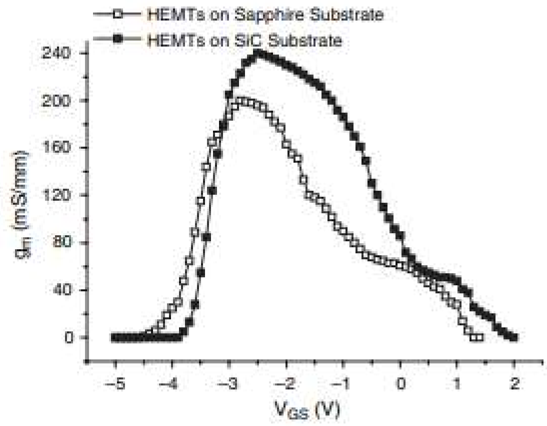

Figure 5 The transfer characteristics of the AlGaN/GaN HEMTs using Sapphire and Silicon Carbide substrates.

The typical transfer characteristics of the HEMTs on SiC and sapphire substrates are shown in Figure 4 and 5. We observe large I_{DS} max and g_m max for HEMT on SiC substrates which is due to the higher values of the 2 dimensional electron gas mobility as compared to HEMTs fabricated on sapphire substrates. In accordance with the DC properties of Aluminum gallium nitride/Gallium nitride HEMTs, the SiC substrate is superior to the sapphire substrate, and these results are lead to a high RF Performa.

These findings are consistent with the substrates' thermal properties of Si, Sapphire and SiC: In comparison to sapphire, silicon is a three times greater heat conductor. Extended flaws that are still present in the AlGaN/GaN structures on silicon, which call for additional development in growth techniques, are likely to be the cause of the maximum current's weaker increase [28].

3. Comparison of Self-Heating Effects in Various GAN-HEMTs

To confirm the substrate impacts on the self-heating effect, the output characteristics of GaN-based HEMTs were measured and shown in Figure 5. The I_D displayed its maximum value when the device was operating on the sapphire substrate, at $V_D =$ 4.0 V. Due to the self-heating effect, which reduces the output power of GaN-based HEMTs, the I_D then fell when the V_D was increased. When the devices were used with an AlN substrate or a Cu film, the I_D increased instead of decreasing noticeably. Cu film outperformed sapphire substrate in terms of I_D improvement by 18% and 47% at V_D = 4.0 V and V_D = 10 V, respectively. This data shows the lower self-heating effect in GaN-based HEMTs having high thermal conductivity substrates than sapphire substrates [29].

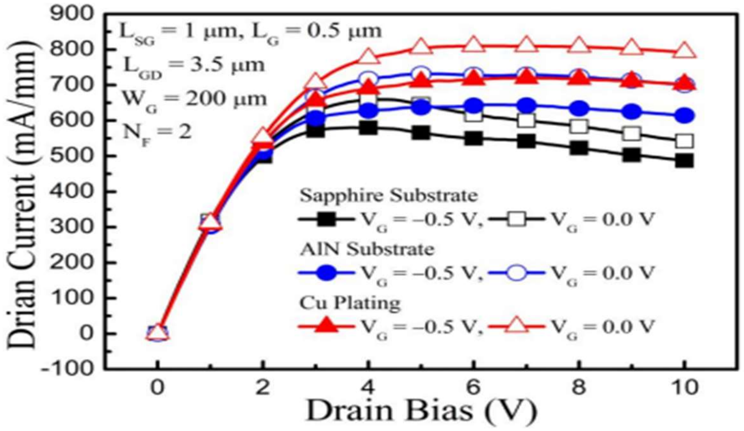

Figure 5**.** Output characteristics of GaN-based HEMTs operated on sapphire substrate, AlN substrate and Cu film. Drain current vs. Drain [29].

In an another theoretical study, Silicon carbide and silicon substrates are found reduce the self-heating effects in the device characteristics due to them having higher thermal conductivities, when compared with the sapphire substrate [30].

5.Results and Discussion

In the present study, the effect of Si, Sapphire and SiC as substrate in the fabrication of HEMT and the consequential enhancement in the characteristics features of device for power device applications has been critically analyzed. Based on the studies undertaken, it has been found that Si, inspite of poor lattice and thermal mismatch with GaN, is the better material that can be used as substrate. It is because, it is characterised by large band gap, high critical electric breakdown field, high electron mobility and velocity, and economic viability. The thermal and lattice mismatch in HEMT is compensated through the growth of heterojunction structure technology in fabrication process of HEMT. It has helped to achieve comparable epilayer device qualities, making them less complex to compare. Due to the Si substrate's good crystalline quality its similarity with the sapphire substrate device dimensions, 2-Dimensional electron gas mobility with high drain saturation current, peak transconductance, and linearity were seen. The High electron mobility transistor on Silicon demonstrated greater stability when compared to sapphire substrate because of the reduced scattering phenomenon at high drain bias (related with the thermal conductivity). While the reduced gate leakage behaviour of the HEMT on sapphire verifies its suitability The High electron mobility transistor on Silicon substrate convenient for cost efficient high-power amplifier applications because to its high stability, linearity, output power, and sustainability of saturation current as well as g_m at higher applied drain voltages. In case of SiC, a superior 2-Dimensional electron gas mobility having higher values of I_D max and g_m max were detected due to SiC substrate's high crystalline quality and the one order lower dislocation density of GaN. SiC-based HEMTs exhibit greater values of the drain current density, the extrinsic transconductance, and the output power density than sapphire substrate, due to the characteristics of high epi-grown quality and outstanding thermal conductivity. As a result, using SiC substrates promises to deliver improved power performance as compared to sapphire, however cost is the key issue.

6. Conclusion

Based on the studies undertaken, it has been found that Si, inspite of poor lattice and thermal mismatch with GaN, is the better material that can be used as substrate in fabrication of HEMT. The High electron mobility transistor on Silicon demonstrated greater stability when compared to sapphire substrate It is because, it is characterised by large band gap, high critical electric breakdown field, high electron mobility and velocity, and economic viability. Using SiC substrates promises to deliver improved power performance as compared to sapphire, however cost is the key issue.

Acknowledgement

Authors are grateful to SGT University authority for their consistent encouragement and support during the course of this work.

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