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Influence of High Temperature on the Electrical Properties of GaN HEMT Devices: A Review

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Abstract

GaN (Gallium Nitride) is one of the fastest-growing broadband semiconductor materials nowadays, and GaN HEMT (High Electron Mobility Transistors) provides a variety of possible uses in the fields of high frequency, high power, high temperature, and radiation resistance. Recently, GaN-based (HEMTs) has been broadly used in rising industries like 5G technology, new smart vehicles, unmanned aerial vehicles, and different applications because of their high power and high resistance. However, because HEMT devices have a high-power density, the self-heating effect will cause the junction temperature of the device will increase dramatically, negatively impacting the device's longevity and dependability. A particular kind of Field-Effect Transistor (FET) that uses a heterojunction structure to improve performance is called a high electron mobility transistor, or HEMT. This work provides a comprehensive analysis of how high temperatures affect electrical properties. Understanding and enhancing the performance of gallium nitride high electron mobility transistor devices requires understanding how high temperatures affect their electrical characteristics. Given the widespread usage of GaN HEMTs in high-frequency and high-power electronic applications, it is imperative to investigate the effects of elevated temperatures on their electrical characteristics.

Keywords: GaN HEMT, AlGaN/GaN HEMT, high temperature, 2DEG.

1. Introduction

As human society has advanced into the information age over the past few decades, the semiconductor industry has accelerated its development and steadily grown to become an essential component of people's daily life. Higher demands have been placed on semiconductor device performance due to the ongoing advancements in science and technology. Unmanned aircraft, 5G technology, new vehicles, and other developing applications have extensively used power electronics devices based on GaN materials like HEMT and MESFET [1-3]. Compared to first- and second-generation semiconductor materials, GaN, a third-generation semiconductor material, has a large bandgap, a high critical breakdown electric field, and a high electron saturation rate. Observations reveal that GaN materials have a critical breakdown electrical field of 3.3 mV/cm and a forbidden bandgap of 3.39 eV, making them ideal for high-frequency and power electronic devices [4-5]. In power applications that demand high breakdown voltage, high-temperature operating capability, and high-power conversion efficiency, GaN-based devices are becoming more and more common because of their wide bandgap energy, high electron saturation velocity, and particularly the high density and high mobility of the Two-Dimension Electron Gases (2DEG) [6-8]. Excellent electrical characteristics include high field breakdown, high field saturation, high thermal stability, and high mobility in GaN-based high electron mobility transistors [9]. These attributes are preferred for applications involving high frequencies. GaN HEMT device is now also utilized in high power switches to achieve improved temperature and breakdown extremes. The steady–state current caused by the two-dimensional electron gas (2-DEG) at thermal equilibrium is the primary issue with GaN-based devices. Typically, this kind of HEMT is called depletion mode HEMT (D-HEMT) or ON HEMT [10]. The first AlGaN/GaN heterojunctions were created in the 90s and were effectively developed by in a study by [11] using metal-organic chemical vapor deposition (MOCVD) on sapphire substrates. The GaN-based HEMT structure was created was first suggested by [12] a year later. The advent of 5G technology has made GaN-based HEMT devices a prominent topic for development in the semiconductor industry in recent years. Two key characteristics of GaN HEMTs are their large concentration of 2DEG gathered at the heterojunction edge and their 3.39 eV forbidden band [13], [14]. At normal temperatures, 2DEG displays highly high electron mobility (>2000 cm^2 /V -S), which provides HEMT devices with superior frequency and power density. The self-heating effect of HEMT devices raises the device junction temperature significantly and degrades its output properties when strong currents pass through them. Reducing the junction temperature of the device can greatly extend the device lifetime because it is well known that the failure of electronics rises with temperature and becomes more noticeable at high temperature [15]. This issue cannot be resolved by conventional package level heat dissipation technologies; instead, GaN HEMT heat dissipation must be enhanced internally in the device. These days, Silicon Carbide (SiC) substrates at high thermal conductivity are typically deployed for GaN HEMTs. However, SiC substrates struggle to meet the demands of high heat dissipation for higher power density HEMT devices; as a result, one of the key strategies for resolving the self-heating issue with HEMT devices is to find alternative substrate materials with better heat dissipation capabilities [1].

GaN HEMT stands for gallium nitride high electron mobility transistor. In this research, the work was divided into several parts: methodology, discussion of results, and conclusion.

2. Methodology

A GaN HEMT can be made to withstand higher temperatures in several ways. The approach will vary depending on the kind of gadget and the electrical properties that require enhancement. Typical techniques include the following:

1. Modifying the device's design might lessen heat generation or increase its heat transfer capabilities. One possible solution is to utilize a substrate with a more scignification thermal conductivity coefficient or to raise the thickness of the GaN layer.
2. A GaN device's electrical or thermal properties can be improved by adding additional layers or materials. For example, a layer of thermal insulating material or more comprehensive bandgap material can be added to increase resistance to high temperatures.
3. The GaN material's characteristics can be altered by heat treatment. Diffusion processing, for instance, can be utilized to raise the impurity concentration in GaN, improving its transport characteristics.
4. GaN may be substituted with other materials. GaAlN or InGaN, for instance, can be utilized to increase endurance at high temperatures.

3. Results and discussion

In this research, the work was divided into four types in terms of structure, and these types were studied in all their specifics, as follows:

3.1 AlGaN/GaN HEMT (High Electron Mobility Transistor) Structure:

Using electro-thermal (Technology Computer Aided Design) TCAD simulations, this work explains the impact of self-heating on the behavior of AlGaN/GaN-based HEMTs produced on sapphire substrate, as shown in figure (1). Due to the inclusion of extra AlN above the device, which serves as a heat spreader, the suggested device, damped with AlN/SiN (Aluminum Nitride/Silicon Nitride) as seen in Fig. (2), exhibits superior thermal performance above the traditional device with SiN damping. The AlN layer in the damping scheme lowers the interface traps at the damping/AlGaN. It is essential to increase the drain current by decreasing the SHEs, according to thermoelectric simulations conducted for various AlN thicknesses (ranging from 0 µm to 25 µm). At room temperature, every simulation was run. Compared to the other devices, the one with 5 µm AlN performs better. While the traditional damping using SiN demonstrated a temperature of 578 K^0, the simulation of the suggested layered damping using AlN/SiN revealed a minimal lattice temperature of 418 K. This cost-effective simulation with the self-heating model and AlN/SiN (LG = 1µm) TCAD (LG = 1µm) revealed a 63% improvement in cross-conductivity and a 60% improvement in drain current density. The device's overall performance has been enhanced, which makes it more stable and dependable for a more excellent range of operations, a desired quality in the high-power industry [16].

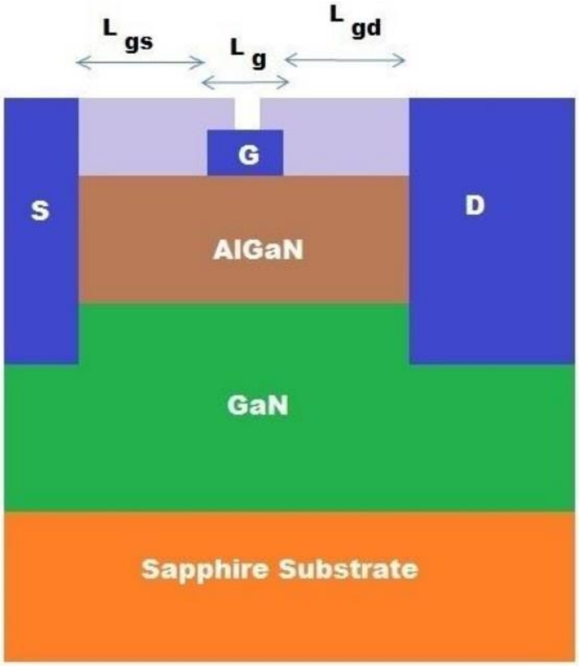


Figure 1: A traditional GaN/AlGaN-HEMT [16].

Figure 2: Suggested device design with the AlN layer on top [16].

As shown in figure (3), AlGaN/GaN HEMTs, or high electron mobility transistors, were investigated for their temperature properties, and the impact of the self-heating effect on these devices was examined. To improve device reliability, reduce the effect of self-heating, and decrease the device temperature, Figure (4) shows a new device construction. The highly heat-conductive diamond and SiC used in the construction instead of silicon and Si3N4 as the device's substrate and passivation layer let the substrate and passivation layer dissipate heat more effectively. Additionally, a hybrid barrier film and field plate are used in the new structure. According to simulation data, compared to the basic traditional structure, the new structure has a peak temperature of around 30% lower, an output current of 47% higher, a conductivity of 28% higher, and a current breakdown rate of 18.22% higher. Consequently, the reliability of GaN HEMT devices is increased by this structure, which can operate at high temperatures and high power [1].

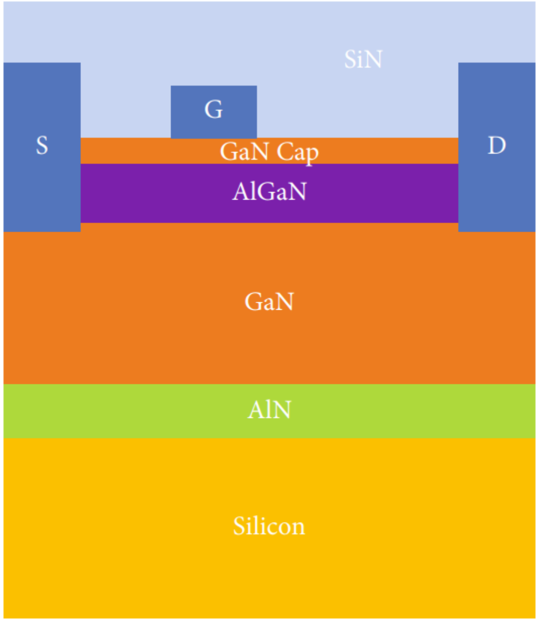


Figure 3 : Conventional Device Structure [1].

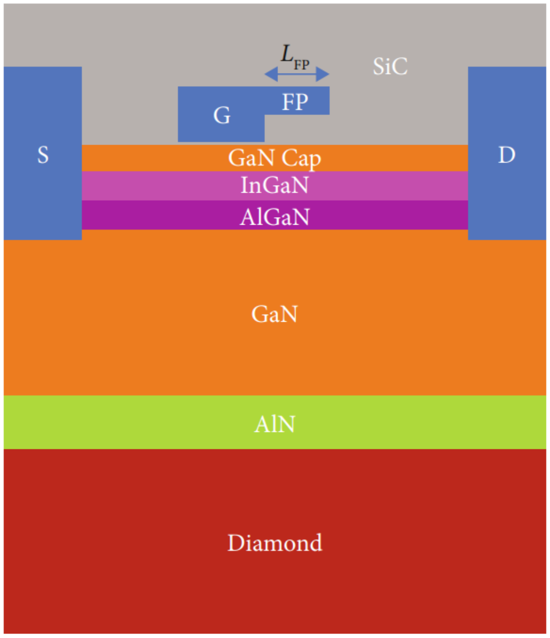


Figure 4 : The Diamond Substrate and the Passivation Layer are SiC [1].

In figure (5), a decreasing aluminum composition graded AlGaN back barrier behind the GaN channel. High performance double heterojunction-based AlGaN/GaN HEMT have been shown. The DH HEMT exhibits noticeably better on-state breakdown voltage and drain current density than a single heterojunction-based HEMT because of the increased electron confinement made possible by the graded back barrier. More intriguingly, the surface states of the HEMTs can be efficiently suppressed by an additional SiNx passivation layer. This results in a nearly constant off-state leakage current and slight gate contact deterioration over a temperature of 25◦C to 150◦C. These outcomes demonstrate the excellence and dependability of graded AlGaN which has been suggested to improve device features for use in tough and high-temperature environments [17].

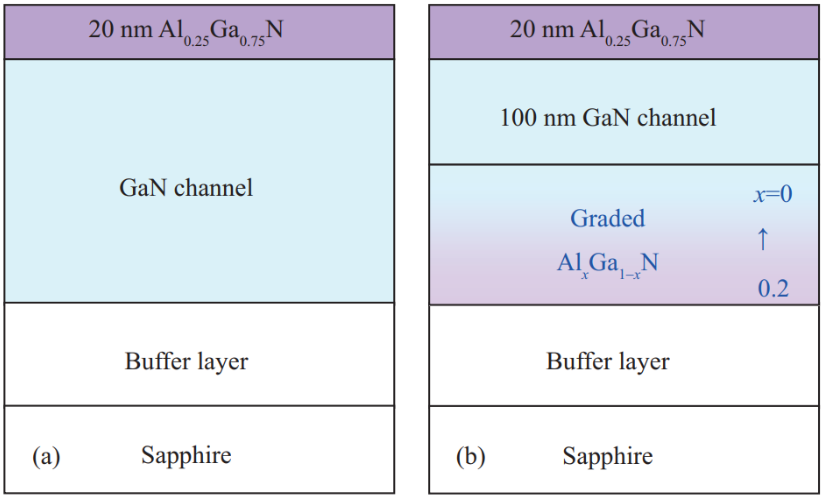


Figure 5: (a) and (b) the SH- and DH-HEMT epitaxial structures [17].

The dependability of electrothermal coupling was examined by exposing the AlGaN/GaN HEMTs to an off-state strain at different ambient temperatures. The experiment's findings demonstrate that a rise in the surrounding temperature causes the device's transconductance and drain current to decrease. When the gadget returned to normal temperature, the decline rate could be restored because it varied consistently with temperature. The decrease in 2DEG mobility brought on by the environment's high temperature was the main contributing factor. The inverse piezoelectric polarization effect, which was exclusive to the electric field, was one of the two components of the device's degradation mechanism. The deterioration rate of the drain current did not appear to be correlated with either temperature or peak transconductance. It resulted from the device's drain current degradation under in-state stress caused by an electric field-driven inverse piezoelectric polarization process. This mechanism did not alter the deterioration of the device under the off-state strain because it was driven by an electric field instead of current, and the temperature has no discernible impact on the applied electric field. Both recoverable and unrecoverable gate leak deterioration were the results. The other was the mechanism of degradation caused by the electric field and temperature acting simultaneously. In addition to causing the leakage current to degrade irreversibly, it also caused a negative shift in the unrecoverable threshold voltage [18].

According to TCAD (Technology Computer Aided Design) simulation results, the self-heating effect will decrease current, essentially consistent with the theoretical study. Furthermore, a comparison is made between the simulation and Monte Carlo results, and the results agree with the latter. The device properties deteriorate due to the drain current decreasing due to the increase in lattice temperature brought on by the self-heating effect of AlGaN/GaN HEMT. Nonetheless, this study's device model an AlGaN/GaN single heterostructure—is relatively straightforward, as shown in figure (6) [19].

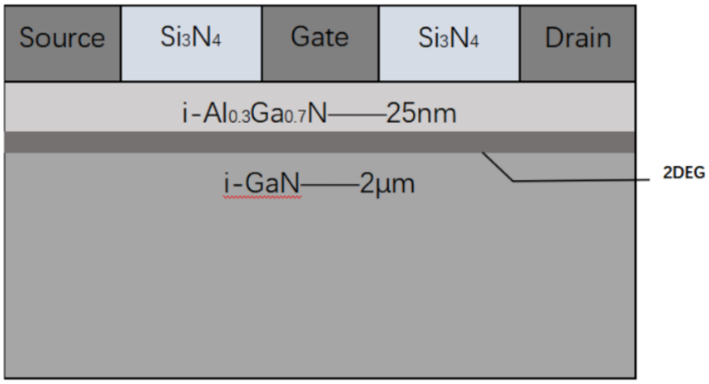


Figure 6: The examined device's cross-sectional diagram [19].

In Figure (7), it was successful in building-AlGaN/GaN HEMT of a partial GaN cap layer. The on-state output, ohmic contact, and transfer properties of AlGaN/GaN HEMTs were evaluated at various temperatures. The sheet resistance rises linearly with temperature, and the ohmic contact shows good high-temperature stability. The saturation current in the output dropped at high temperature. In the meantime, the degradation of the saturation current in the production of AlGaN/GaN HEMTs with GaN partially capped is lessened compared to the traditional AlGaN/GaN HEMTs. This can be attributed to the optimization of both the electric field distribution and the thermal field distribution. [20].

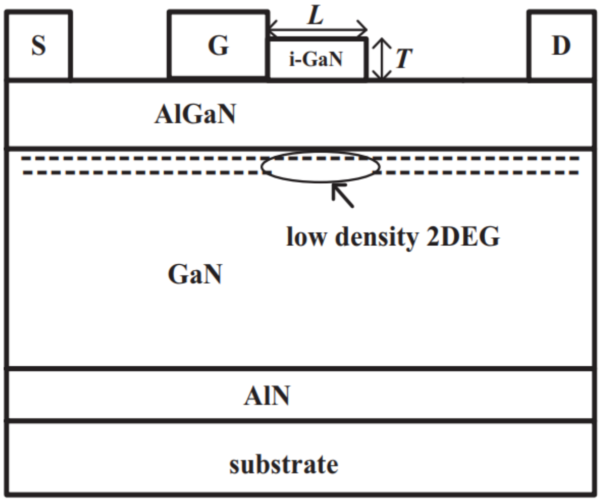


Figure 7. Schematic representation of the Suggested PCL- HEMTs [20].

Thorough simulations have been performed on three different passivation materials: silicon nitride, silicon dioxide, and aluminum oxide, all of which have a thickness of roughly 400 nm, as shown in figure (8). The output characteristics show a significan reduction in output current due to self-heating, but the transfer characteristics show no effect from isothermal simulation. Observations of the channel temperature of AlGaN/GaN HEMT for various passivation materials have shown that it is 448k, 456k, and 471K for Al_2O_3, SiN, and SiO_2, respectively. Aluminum oxide has the lowest temperature. The performance and dependability of the equipment can be assessed using this investigation [21].

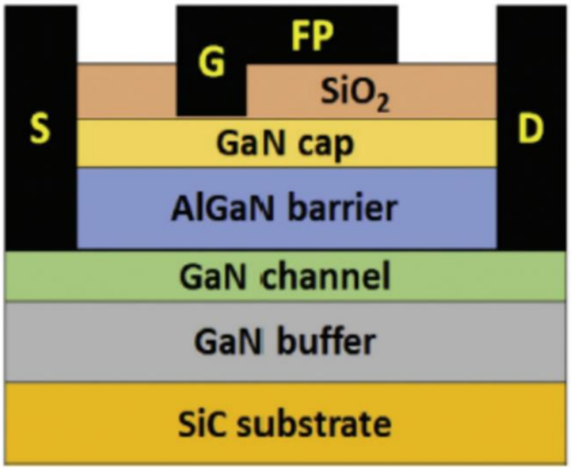


Figure 8: AlGaN/GaN HEMT Schematic with SiO2 Passivation Material [21].

The electrical characteristics of Al0.25Ga0.75N/GaN HEMTs have been investigated for a wide range of gate lengths. As seen in figure (9), studies were carried out at room temperature to investigate the effects of gate length on several device characteristics, including the ideality factor (n), maximum transconductance (gm max), barrier height (Φb), pinch voltage (Vp), and maximum drain current (Ids max). According to the results, decreasing the gate length may improve device performance as the transconductance output current for the device rose. For (AlGa)N/GaN HEMT, a short gate length seems to be a good way to achieve a uniform Schottky barrier and enhanced electron transport [22].

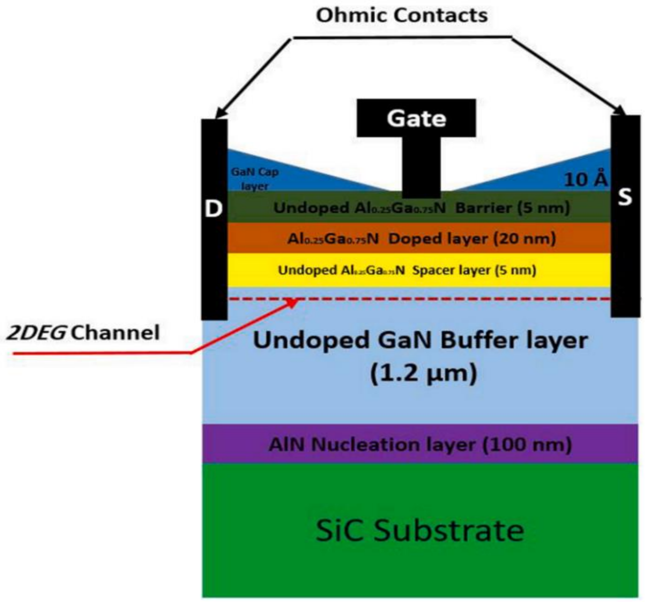


Figure 9: Al0.25Ga0.75N/GaN/SiC HEMT cross-section. (2DEG); source (S); drain (D) [22].

In figure (11), direct-current (DC) properties of AlGaN/GaN HEMTs constructed on diamond and Si, as shown in figure (10), with identical device dimensions were studied. For the GaN-on-Si HEMT, thermally-induced negative differential output impedance was seen in the saturation region of DC; at similar power densities, this was insignificant for the GaN on diamond substrate, which is consistent with lower thermal resistance. The GaN on-diamond device has a more excelant contact resistance. GaN-on-Si HEMT has a threshold voltage of -3.5 V, whereas GaN-on-diamond HEMT has a value of -3 V. In contrast, at the same degree of power dissipation, the current at saturation zone of the GaN HEMT exhibited minimal droop. However, because of the increased layer resistance and contact impedance in the GaN-on-diamond epitaxial structures, the maximum current for the GaN HEMT is less than GaN on silicon [23].

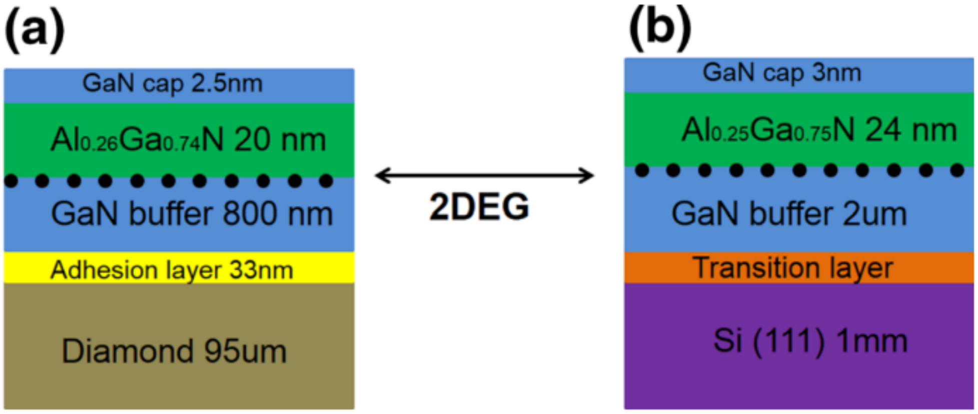


Figure 10: Schematic of the HEMTs' cross-sections and epitaxial layer structure: sample A in (a) and sample B in (b) [23].

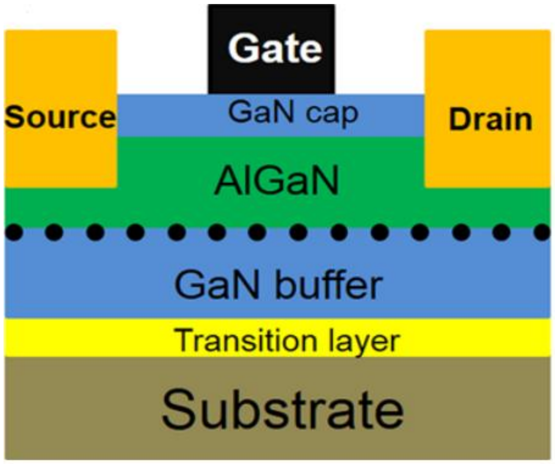


Figure 11: Structure of the AlGaN/GaN HEMT Device [23].

It was established that AlGaN/GaN metal-insulator-semiconductor (MIS-HEMTs) operating in both enhancement mode and depletion mode, as shown in figure (12) and figure (13), could function at high temperatures. At 400 ◦C, a high Ion/Ioff ratio of around 10^8 was produced using the circular structure device to suppress off-state current. In order to create a reliable, normally-off operation that could withstand temperatures of up to 400 ◦C, atomic etching layer was utilized to produce the gate structure in the Enhancement mode device. Strain relaxation caused a positive threshold voltage change in the Depletion mode device during the operation at high temperature and after it cooled to ambient temperature. However, the Enhancement mode device's threshold voltage remains almost constant when heated and cooled because of the extremely thin AlGaN layer that is kept behind the device's gate. The

D-mode and E-mode devices create a straight coupled field effect transistor logic inverter, which demonstrated steady functioning up to 400 ◦C [24].

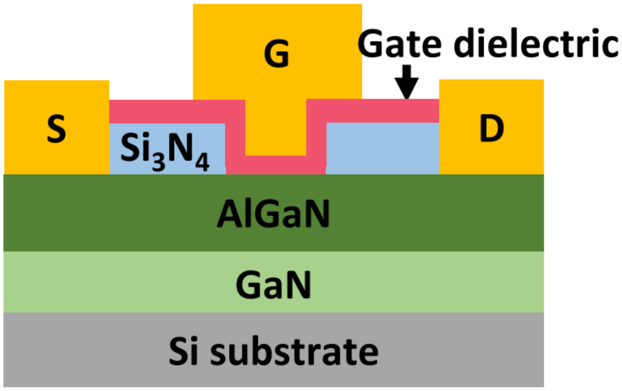


Figure 12: Diagram of a circular AlGaN/GaN MIS-HEMT in D-mode [24].

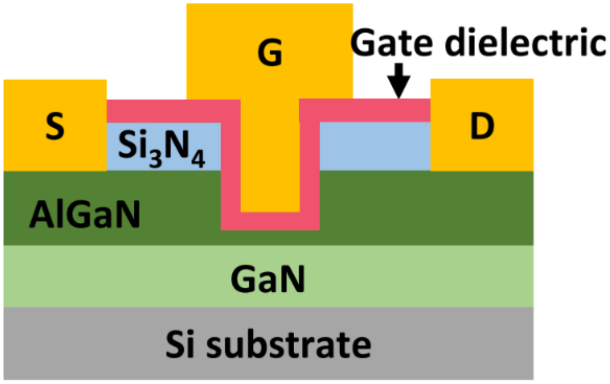


Figure 13: Diagram of a Circular AlGaN/GaN MIS-HEMT in E-Mode [24].

In order to explain the process of internal charge modulation and lower the junction temperature of the AlGaN/GaN HEMT, a 2-D temperature distribution model was presented, as shown in figure (14). A hot spot is created in the thermal field by the etched AlGaN layer, which modifies the channel 2DEG distribution and successfully lowers the temperature while achieving a more uniform temperature distribution. In order to explain how structure parameters affect temperature optimization, a quantitative analysis of the temperature structure has been provided. It has been found that a deeper etching depth is advantageous for lowering junction temperature and that an etched AlGaN/GaN HEMT not only efficiently lowers channel junction temperature but also optimizes temperature field distribution, which helps to reduce the self-heating effect and enhances high-temperature stability. The model's applicability is demonstrated by experimental testing and simulation findings. The model's ability to accurately depict the optimization of temperature of AlGaN/GaN HEMTs using the gate edge etching process is concluded [25].

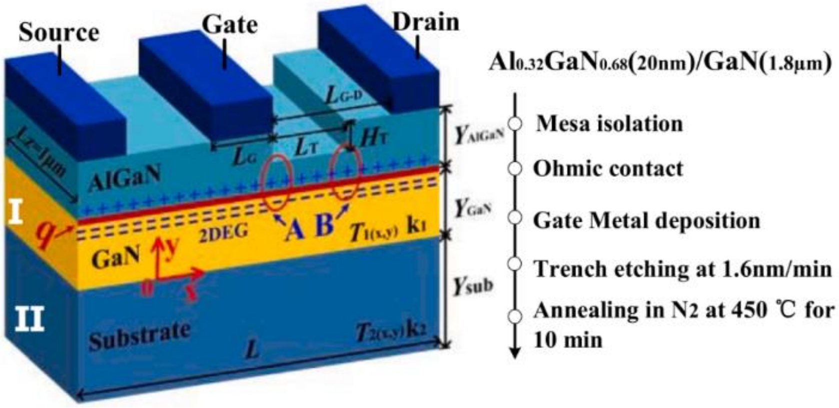
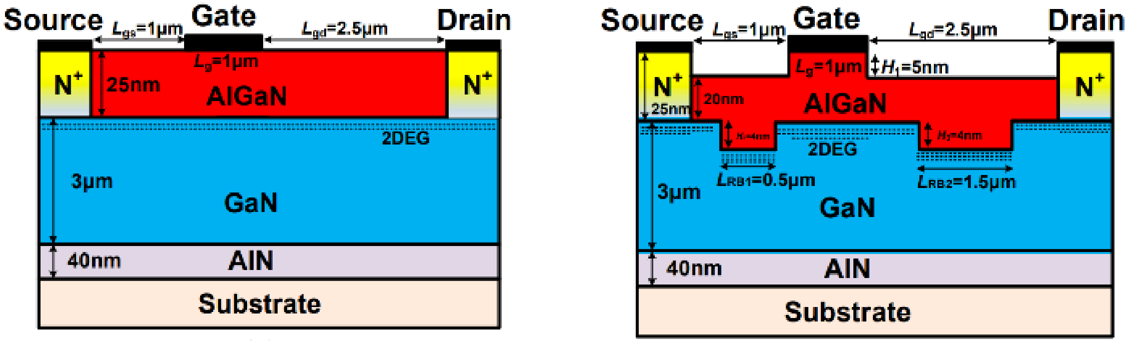


Figure 14: AlGaN/GaN HEMTs in three dimensions with the etched AlGaN layer [25].

For high-energy-efficiency applications, a new AlGaN/GaN (HEMT) with a High Gate and a Multi-Recessed Buffer (HGMRB) is presented, as shown in figure (15). By using SiC as the substrate, the self-heating effect is significantly diminished. The suggested HGMRB HEMT has a barrier zone 6nm lower below the drain, source, and gate electrodes than the traditional HEMT, creating a high gate. The high gate is separated from the source/drain by a barrier zone that is 20 nm height. Both devices have a buffer layer height of 3 µm. The HGMRB HEMT's buffer layer creates two recessed areas on the left and right. Technology computer-aided design and Advanced Design System (ADS) simulations are used to study the mechanism of the device. The widths of the sections were 0.5 µm and 1.5 µm, respectively. However, the depth is 4 nm. The buffer layer of the new structure contains two sections. The gate is 5 nm larger than the barrier layer. Compared to the traditional HEMT, the HGMRB HEMT has a somewhat lower drain saturation current. The HGMRB HEMT and conventional HEMT had maximum drain saturation currents of 550.26 mA/mm and 609.32 mA/mm, respectively, at Vgs = 0V and Vds = 20V. These currents were lowered by 59 mA/mm, making the saturated drain current of the novel structure 9.68% lower than that of the traditional structure. Similarly, the novel structure's saturated drain current was 11.73% lower than the conventional structure with Vgs = 0 V and Vds = -1 V. Because of the HGMRB construction, the channel region has two recessed areas. The discontinuous channel region impedes the channel current; the more profound the buffer region's recess depth, the lower the channel current. At the same time, the barrier layer's thickness is directly correlated with the channel region's two-dimensional electron gas (2DEG) concentration. The channel current will be lower because the HGMRB structure's barrier layer is less than the traditional HEMT's. The maximum drain saturation current of the HGMRB was somewhat lower than that of the conventional HEMT when the two aforementioned criteria were combined. In the buffer region, two recesses were created to prevent the channel current from drastically decreasing; the depth of the recessed area was not very significant. The HGMRB HEMT's maximum drain saturation current and transconductance both marginally drop, according to the TCAD simulation findings. However the breakdown voltage increases by 16.7%, and the gate-to-source capacitance falls by 17%. The gain of the new structure is superior to that of the traditional HEMT. The HGMRB HEMT guarantees a high output power density in radio frequency (RF) simulation, with findings showing that it has 90.8%, 89.3%, and 84.4% power-added efficiency at 600 MHz, 1.2 and 2.4 GHz, respectively. The findings indicate that compared to the standard HEMT, the HGMRB HEMT has a higher chance of achieving high energy efficiency [26].



(a) (b)

Figure 15: Diagrammatic cross sections of (a) the traditional (HEMT) and (b) the proposed (HGMRB) HEMT [26].

3.2 GaN HEMT (High Electron Mobility Transistor) structure:

To investigate the electrical, thermal properties and heat transfer mechanism of stacked chips, a double-layer stacked GaN MISHEMTs structure was created. First, a room temperature comparison is made between the electrical properties of single-layer and double-layer GaN MISHEMTs, as seen in figure (16-a) and figure (16-b). When subjected to identical conditions, double-layer GaN MISHEMTs have an output current twice as high as single-layer GaN MISHEMTs; nevertheless, their off-state current is significantly greater. In the meantime, there is no discernible difference between the single-layer and double-layer GaN MISHEMTs' threshold voltages. Next, it also looks into how temperature affects the electrical properties of double-layer GaN MISHEMTs. The device's output current dropped, its off-state current increased, and its threshold voltage steadily moved adversely as the temperature increased from room temperature to 150 °C [6].

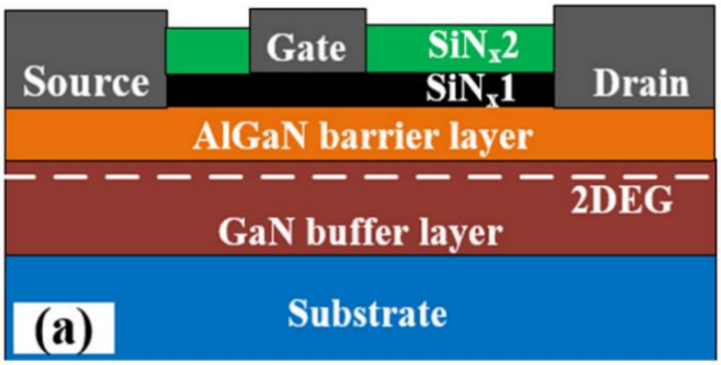


Figure 16a: **The GaN MISHEMT device structure [6]**

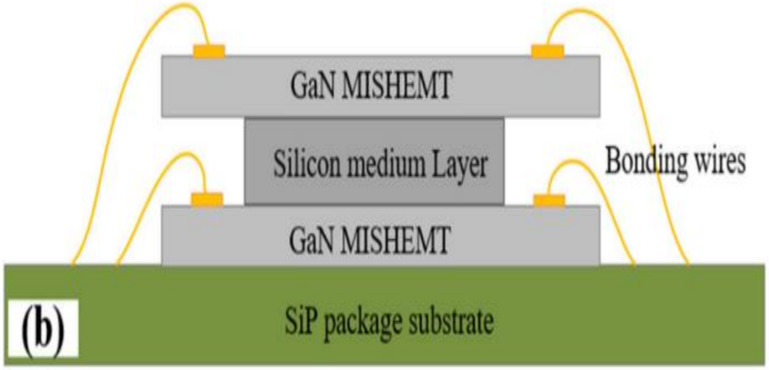


Figure 16b: GaN MISHEMT in two layers [6]

The electrical parameter drain current of a (HEMT) based on (GaN) with a SiC substrate and field plate was analysed, as seen in figure (17). Since channel temperature causes the device's electrical performance to deteriorate, it is employed as the primary parameter. Based on the temperature profile, the study was conducted using technology computer-aided design (TCAD) simulation software. In figure (18), the maximum drain current at self-heating is 0.76 A with Vg = 0 V, and the maximum drain current with zero gate voltages, Vgs and Vds, of 20 volts. In figure (19), the drain current drops to 0.52 A at Vds of 12 V and reaches Vg = -1 V. At Vds = 12 V, the line and drain current equivalent temperatures at self-heating are the same. The drain current drops to 0.31 A and 19 V at Vds of -2 V. The AlGaN/GaN

HEMT on SiC layer works better at lower gate bias with more resistance to the self-heating effect since the equivalent temperature line and drain current with self-heating are the same at Vds = 19 V. This suggests that with lowered gate bias, the self-heating effects in the device decrease. This represents the AlGaN/GaN HEMT's lattice temperature distribution with the field plate with gate bias Vg = 0.0 V, and drain bias Vd = 20 V. The edge of the gate, faces the drain, and the minimal area just below the gate have the most sginificat-temperature (hot spot) [27].

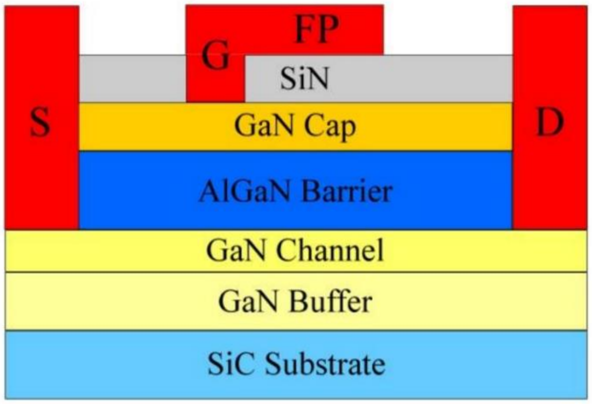


Figure 17: 2D Field Plate GaN HEMT Schematic [27]

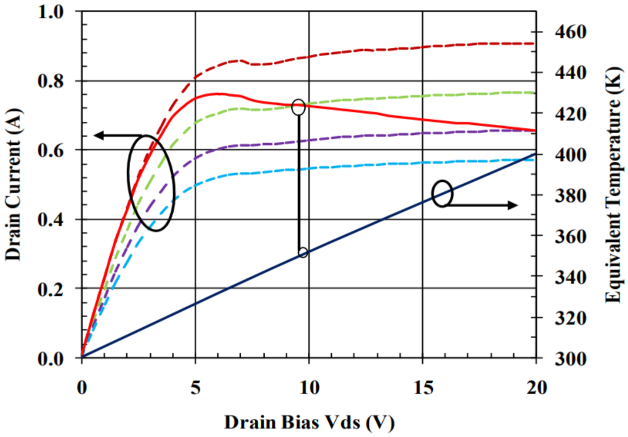


Figure 18: The comparable channel temperature extraction curve Teq (Equivalent Temperature) at Vds= 20 V and Vgs= 0 V [27].

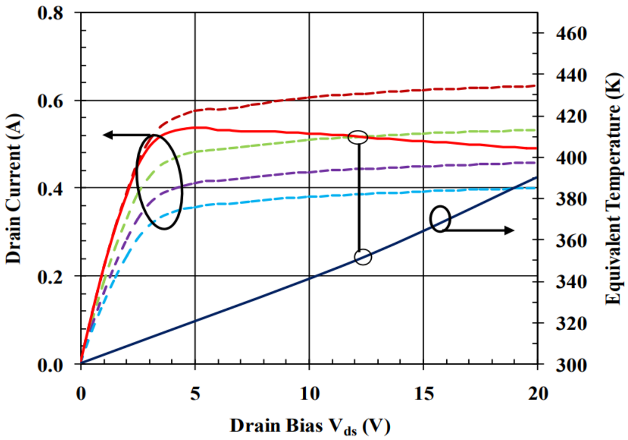


Figure 19: Curve illustrating how equivalent channel temperature is extracted Teq at Vds = 20 V and Vgs = -1 V [27].

Systematic research has been done on the device technologies and AlGaN/GaN HEMT performances utilizing Nanocrystalline Diamond Capping (NDC) layers, as shown in figure (20). A 3-step diamond etching process and a 20 nm SiN isolation layer were developed to enhance the technical challenges of the gate length shorter than 0.5 µm and the AlGaN barrier protection. The diamond gate approach was adopted to determine the growth of NDC layers and their compatibility with the Schottky gate of GaN devices. Successful preparation of the 0.3 µm gate length GaN HEMTs with NDC and traditional SiN passivated structures has been accomplished; meanwhile, the electrical properties and heat dissipation performance have been assessed. The thermal test result indicates that NDC-GaN HEMTs have a 21.4% lower thermal resistance than conventional SiN-GaN HEMTs, indicating that the NDC significantly affects the heat transfer pathways for GaN HEMT applications. The simulation method reveals the heat transfer mechanism for NDC GaN HEMTs, consistent with experiment results.

Furthermore, compared to SiN-GaN HEMTs, the NDC GaN HEMTs exhibit superior output, low signal gain, and cut-off frequency. The cut-off frequency was 34.6 GHz is 1.8% higher than that of SiNGaN HEMTs, particularly in the areas of current-voltage (VGS = 1V) and low signal gain (10 GHz), which demonstrate improvements of 27.9% and 36.7%, respectively. This study's overall findings indicate the superior qualities of the nanocrystalline diamond cap layers for AlGaN/GaN HEMTs in radiofrequency applications [28].

Figure 20: Diagram of the nanocrystalline diamond-based GaN HEMTs [28].

A diamond layer, diamond heatsink, and InGaN insert layer make up the new architecture, which changes the device's composition and structure. Because of the diamond heat dissipation layer and InGaN layer designs, the device temperature was successfully reduced and the electron mobility in the channel was enhanced. There has been a 35% decrease in the device's maximum temperature, from (518 – 335) K. The breakdown current is improved by 35%, and the output current value is raised by 61%, from 0.85 mm^{-1} to 1.37 mm^{-1}. Simultaneously, the device's maximum conductivity improves by 37%, from 240 $mS\ mm^{-1}$ to 329 $mS\ mm^{-1}$. As a result, this paper's construction enhances GaN HEMT's electrical characteristics, as shown in figure (21) and figure (22) [29].

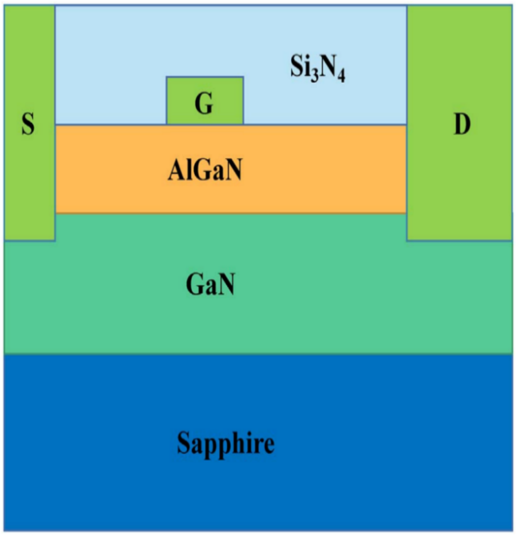


Figure 21: Conventional GaN HEMT device [29].

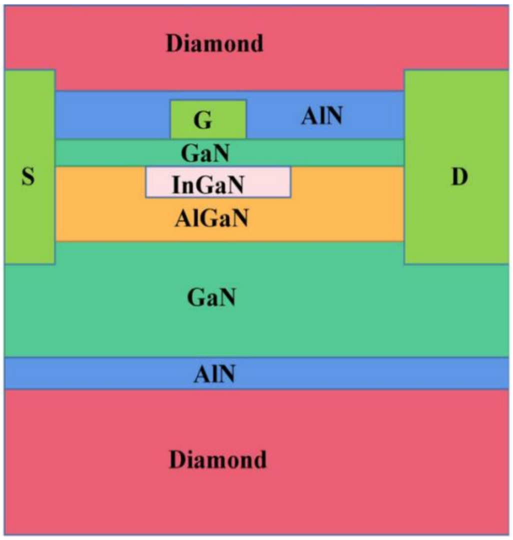


Figure 22: The structure of the InGaN insertion layer [29].

It was investigated how temperature affected the p-GaN gate in HEMT boost mode, both with and without a separator, as shown in figure (23). The DC properties of the HEMT structure, which has a p-type gate, have been examined at Room Temperature (RT). It is found that when the spacer layer is removed, on-current rises noticeably (1.2 times higher). The impact of temperature fluctuations has been examined in terms of threshold voltage (Vt), leakage current (Ioff), on-current (Id), and on-resistance (Ron) in both devices. According to modeling results, the p-GaN gate HEMT without a spacer layer improves device performance at different temperatures. It is discovered that in the Quantum-Well (QW) area, high mobility (Figure 24) and high carrier density (Figure 25) lead to increase on-current in the absence of a spacer. But for the same reason, the leakage current is slightly higher. In addition, the device without a spacer has a perfect saturation zone and gives greater on-current (Figure 26) than the device with a spacer, according to the output parameters [10].

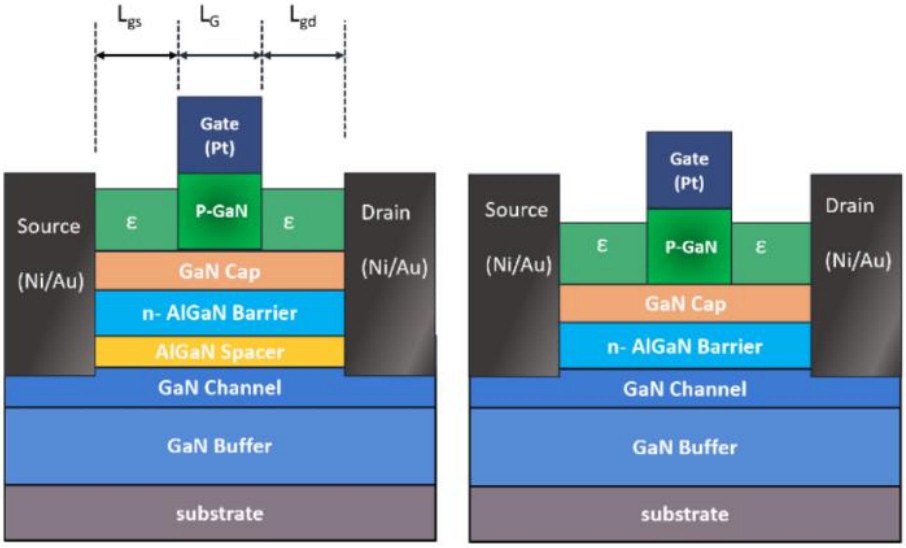


Figure 23: Diagram of the p-GaN Gate HEMT a) spacer is used; b) is not used [10].

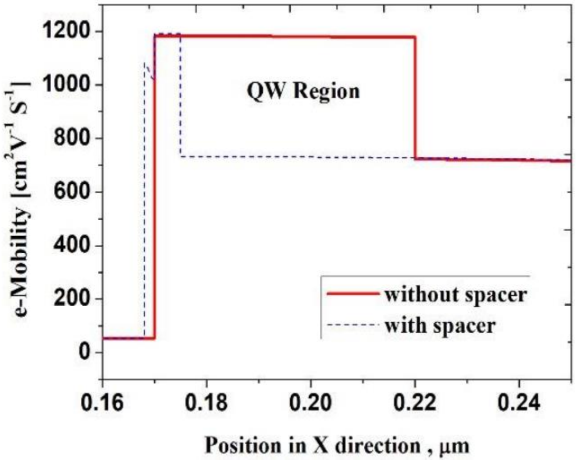


Figure 24: Electron carrier mobility in the (QW) area at 300 K^0 is compared between the two devices. More mobility (1182 cm^2v -1s -1) is reported without spacer p-GaN HEMT with spacer p-GaN HEMT [10].

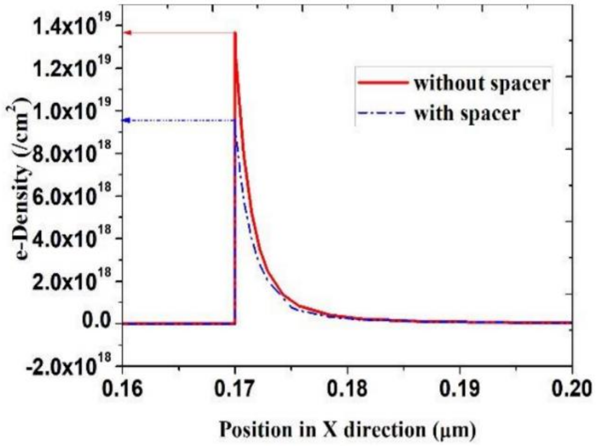


Figure 25: Comparing the two devices' carrier (electron) densities in the QW area at 300 k. p-GaN HEMT with no spacer provides a higher density (1.38 x 1019 /cm2) than p-GaN HEMT with spacer [10].

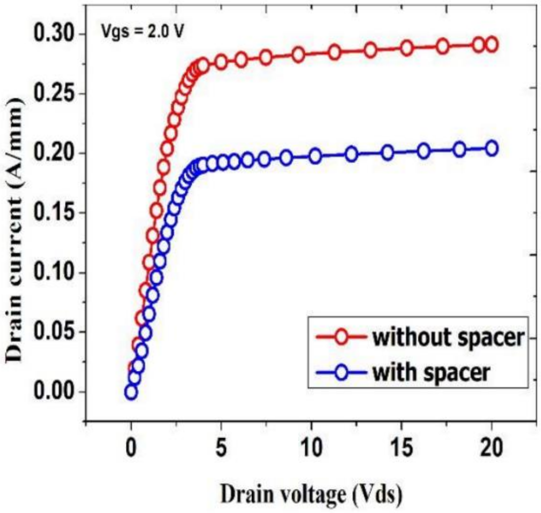


Figure 26: Drain voltage (Vds) vs. drain current (Id) for a p-GaN HEMT (with and without spacer) at 300 K^0 [10].

The development of GaN-on-Diamond technology reduces the overall thermal resistance of the near junction area of GaN HEMTs by placing a diamond substrate with high thermal conductivities right next to the chip's hot spot, as shown in figure (27), hence minimizing temperature rise. Nevertheless, the GaN-on-Diamond HEMT technique adds a thermal border resistance to the GaN/diamond interface layer. This TBR is a component of the GaN chip's overall conduction thermal resistance, affecting the device's heat dissipation capacity. The temperature variation that declines in the order of ΔT1, ΔT2, ΔT3 and ΔT4 of the same TBR is a manifestation of the reduction of the junction temperature caused by the rising diamond thickness with a decreasing trend at a constant TBR. For example, at a TBR of 3 m2K/GW, the corresponding values are 5.5 K, 3.3 K, 2.2 K, and 1.5 K, respectively. In the meanwhile, the value at ̧T4 under various TBRs remains nearly constant, ranging from 1.5 K to 1.6 K in the 3-140 m2K/GW TBR range that was studied. This pattern can be seen in the values of ΔT1, ΔT2, and ΔT3 under various TBRs, showing that the TBR is not a limiting factor for the rule governing the influence of diamond layer thickness on the junction temperature [30].

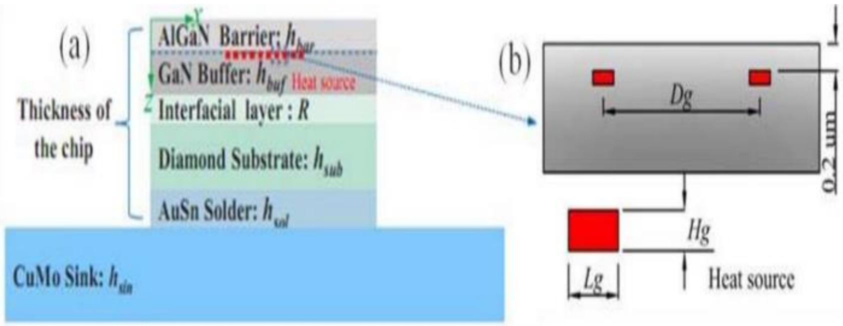


Figure 27: Cross-section schematic; (b) the multi-finger AlGaN/GaN HEMTs heat source **[30].**

In a short gate length GaN HEMT, the self-heating effect-induced current degradation was proposed to be measured by the equivalent channel temperature, as shown in figure (28). In addition to being appropriate for thermoelectric compact modeling, the equivalent channel temperature's bias independence elucidates the physical significance for the channel temperature obtained using indirect electrical approaches. Conversely, the electrical performance of GaN HEMTs with short gate lengths is not determined by the maximum channel temperature at the drain-side gate edge and exhibits a strong bias dependency. Additionally, a condensed field- and temperature-dependent electron transport model has been put forth that sufficiently explains the self-healing. The departure of the equivalent channel temperature of the maximum channel temperature was discovered to be caused by the velocity saturation resulting from the high electric field in most of the gated channel. The primary reason for the current deterioration of HEMTs with short gate lengths is the resistance increase brought on by the source-access region's self-heating. Device engineers may profit from the data's insights while designing and building the HEMT shape for optimal thermal performance [31].

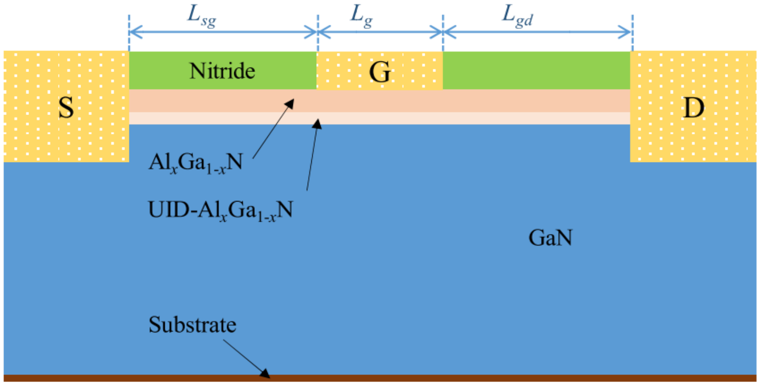


Figure 28: Diagram for the GaN HEMT [31].

The experimental results were used to build the boost-mode p-GaN/GaN HEMT gate, as shown in figure (29), and the thermal and electrical effects of high-power microwaves and self-heating were studied. The HPM (high power microwave) effect is simulated, the device's thermal behavior is examined, the hysteresis phenomenon's mechanism is clarified from the standpoint of the dynamic heat dissipation capacity, and it is determined that the self-heating effects and HPM effects differ in two ways: The first is that the two have differing tendencies to generate temperature changes. Whereas the temperature difference under the HPM effect exhibits an upward sinusoidal-shaped pattern, the temperature difference under the self-heating effect exhibits a linear growth trend. The two will have distinct mechanisms and temperature-rising rates due to their respective working modes. There was a 108-fold difference in the rate of temperature rise between the self-heating test (2 V, DC voltage) and the HPM test (300 V, 5 GHz sine wave) due to variations in the gate voltage bias. The goal of the HPM assault is to rapidly heat and burn the equipment by producing high-energy electromagnetic radiation within the second time scale. Another distinction is the distribution and quantity of hotspots. According to the damage mechanism study, the device's gate causes the right and left margins of the p-GaN area to break down due to HPM action. This generates a significant breakdown voltage value that lowers the device's temperature. Sharp rises and even scorches. The modeling results show two potential damage areas that are consistent with the experimental data: the gate terminals close to the drain and the source caused by HPM. This is a crucial resource for learning about HEMT damage site prediction technology and improving dependability [32].

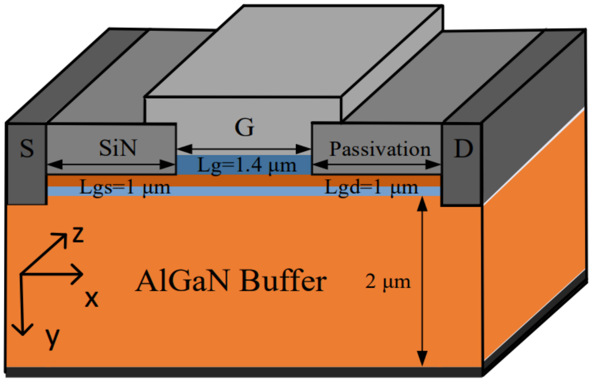


Figure 29: Cross-Sectional Diagram of p-Gate in the Enhancement Mode GaN/AlGaN HEMT [32].

3.3 BGS (Basic GaN on SiC) HEMT Structure

Cross-structure and trench filled with copper were used to enhance heat dissipation. Therefore, the thermal structures were built using a simple T-shaped HEMT, as seen in figure (30). Using thermal devices packed with copper lowers the overall grid temperature in the 2-DEG channel. Applying the thermal structures to the GaN HEMTs reduced the time needed to attain the maximum network temperature, as demonstrated by transient thermal analysis, which verified that the maximum junction temperatures were smaller for the copper-filled thermal devices. The simulation outcomes suggest that CTV (Copper-filled Thermal Via) can enhance GaN HEMTs' thermal management. SHE (Self Heating Effect) decreased the total conductivity and the drain current. Two distinct copper-filled thermal devices for the SiC substrate to regulate the heat produced by the SHE. The total drain current and maximum conductivity improved and stabilized the saturation current due to the application of the copper-filled thermal structure compared to the BGS structure. The DC characteristics of the two copper-filled thermal devices were simulated using SHE and compared with those of the BGS HEMT. However, by lowering the total grid temperature within the device's 2-DEG channel, the extra heat sinks created by filling the copper increased the breakdown voltage by decreasing the gate leakage current. Reducing the total amount of heat produced during device operation was made possible by intersecting thermal structures packed with copper [33].

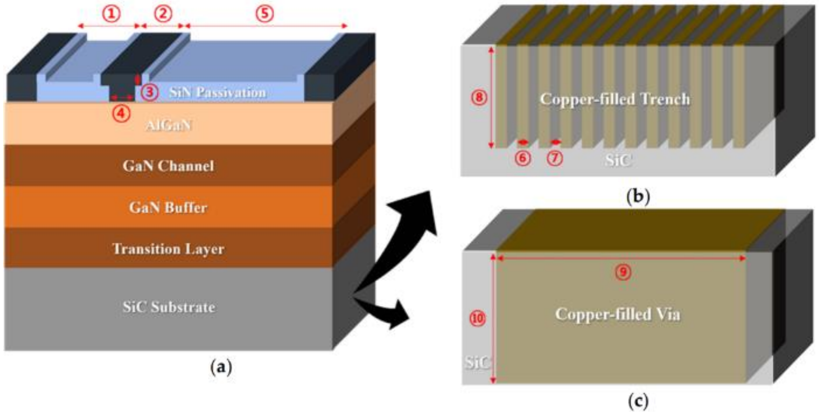


Figure 30: Basic AlGaN/GaN on SiC, copper-filled thermal trench, and copper-filled thermal via in the SiC substrate (BGS) comprises the AlGaN/GaN HEMT structure [33].

3.4 DMG (Dual Metal Gate) HEMT Structure

In figure (31), using electrothermal simulations, the electrical and thermal properties of AlGaN/GaN HEMT devices on diamond substrates with the Dual Metal Gate structure are examined and contrasted with those of devices with the traditional Single Metal Gate structure. The DMG construction may efficiently increase the transconductance with the devices' output current. The DMG devices were found to have a maximum gm value of 0.164 S/mm, which was 10.0% greater than the SMG devices' 0.149 S/mm. Furthermore, the DMG structure alters the devices' channel's electric field distribution, which lowers the electric field's peak at the drain side's Gate 2 edge. This lessens phonon and electron scattering in the channel. As a result, the structure with the DMG structure has a lower peak heat generation.

Furthermore, some heat production that extends with the channel and then into the GaN layer is facilitated by the electric field peak on the Gate 1 edge of the devices at the DMG structure. When comparing AlGaN/GaN HEMT devices with the SMG structure to those with a DMG structure, the maximum temperature rise is reduced by more than 11%. These findings imply that AlGaN/GaN HEMT devices with the DMG structure are a viable option for high-power electronics applications as it efficiently enhances the electrical properties and lowers the hot spot temperature of these devices [34].

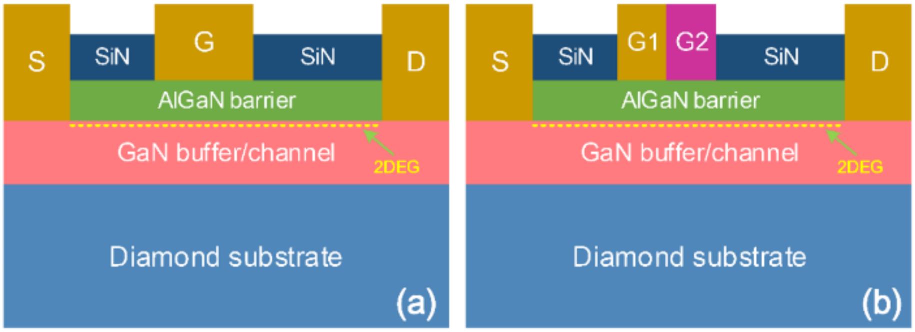


Figure 31: AlGaN/GaN HEMT devices with the SMG and DMG structures [34]

Table 1: Comparison of Different Device Structures and Performance Evaluation.

Device	Temp.	Output Current	Breakdown Voltage	Ref.
AlGaN/GaN-based high-electron Mobility	578k to 418k	Demonstrated a 60% increase in drain current density.	______	[16]
AlGaN/GaN HEMT	lowers the temperature by around 30%	ups the output current by 47%	______	[1]
DH-HEMTs based AlGaN/GaN	______	Shows a markedly enhanced on-state drain current density	off-state breakdown voltage in relation to HEMT based on a single heterojunction (SH).	[17]
AlGaN/GaN heterojunction structure	______	A rise in the surrounding temperature causes the device's transconductance peak and drain current to fall.	______	[18]
AlGaN/GaN HEMT	Temperature increases at the lattice	drain current is a decrease	______	[19]
AlGaN/GaN HEMTs	Temperature rises	Decreases in output saturation current	______	[20]
AlGaN/GaN high electron mobility transistor (HEMT)	The output current of two-layer GaN MISHEMTs is double that of one-layer GaN MISHEMTs.	reduction in drain current	______	[21]

(Al,Ga)N/GaN high-electron-mobility	______	Increase the output current by reducing the gate length.	______	[22]
AlGaN/GaN HEMTs	______	Compared to GaN-on-Si, the maximum current of GaN-on-diamond HEMT is less.	______	[23]
AlGaN/GaN MIS-HEMTs	In D-mode, temperature increases	The output drain current in D-mode is 195 mA/mm at 400 ◦C. Large max. Current (218 mA/mm) in E-mode	______	[24]
AlGaN/GaN HEMT	enhanced temperature field distribution, which contributes to enhanced stability at high temperatures	______	______	[25]
AlGaN/GaN HEMT	______	Maximum drain saturation current and transconductance both marginally decline.	increase 16.7%	[26]
GaN MISHEMTs	From room temperature, the temperature rose to 150 °C.	Double-layer GaN MISHEMTs have an output current twice as high as single-layer GaN MISHEMTs.	______	[6]
Field Plate GaN HEMT	At the gate, edge is the highest temperature	Maximum drain current is 0.76 A	______	[27]
GaN HEMTs with nanocrystalline diamond passivated structure	NDC-GaN HEMTs have a 21.4% lower thermal resistance than SiN-GaN HEMTs, which are more traditional.	Max. (IDS) traditional SiN-GaN HEMTs are 743.28 mA/mm, whereas the highest IDS of NDC-GaN HEMTs is 950.45 mA/mm at VGS = 1 V.	______	[28]
conventional GaN HEMT	35% decrease in the device's max. Temp., from 518 K to 335 K.	current collapse is improved by 35%, and the output current is raised by 61%, from 0.85 A mm−1 to 1.37 A mm−1.	______	[29]

p-GaN HEMT	As the temperature rises, on-current (Id) deterioration increases.	Deterioration of on-current (Id).	______	[10]
GaN-on-Diamond HEMTs	By thickening the diamond, the junction temperature is decreased.	______	______	[30]
GaN HEMT	______	The primary cause of the current deterioration of short gate length HEMTs is the rise of self-heating resistance in the source access area.	______	[31]
GaN HEMT	The self-heating effect, Temp. difference demonstrates a linear growth trend when the HPM effect is present, and the temperature difference shows a gradual trend in the form of a sinusoidal signal.	______	______	[32]
SiC substrate of the BGS HEMT	Reducing the total amount of heat produced during device operation was made possible by inserting thermal structures packed with copper.	Using a copper-filled thermal structure instead of a BGS structure improves the stability of the saturation current and total (Id)	Raising breakdown voltage.	[33]
DMG structure	The DMG structure has a temp. rise of 46.0 K, while the SMG structure devices have the max. temp. rise of 51.8 K. The DMG structure devices have a peak temp. rise that is approximately 11.2% lower than the SMG structure devices.	The DMG construction may efficiently enhance the O/P current of the devices.	______	[34]

4. Conclusion

GaN HEMT devices have many applications in high-power and high-frequency fields. Despite the tremendous advances in the development of GaN HEMT devices, the problem of thermal reliability is becoming increasingly critical due to the self-heating effect of the device, which leads to high channel temperature and failure to apply high power. Every study has reported on how high temperature affects the electrical properties of GaN HEMT, including how high temperature affects device reliability and many other effects. The first type, the AlGaN/GaN HEMT structure, can handle frequencies up to GHz and is helpful in driving RF amplifiers and communication equipment. It is stable under harsh operating conditions due to its high thermal resistance. It is suitable for high-power conversion applications due to its high efficiency. It is used in high-voltage applications, so its breakdown voltage is lower than other designs. More precision is needed in its production to ensure the quality of the AlGaN and GaN boundaries. Meanwhile, the GaN HEMT structure does not require high-frequency performance and can handle low and medium-voltage applications. It also has good resistance to environmental corrosion, but electron mobility and density may be poor compared to other designs. Compared to silicon and other materials, SiC has better thermal conductivity, which enhances the performance of the BGS HEMT structure at high temperatures. Due to its high breakdown voltage, the SiC structure can be used in radar and other high-voltage applications such as industrial power systems. Due to its high cost compared to other materials, SiC increases the cost of manufacturing devices. The DMG structure can help enhance low-voltage response and reduce leakage currents, and it is often used in communications applications. However, the two-gate manufacturing method is more complex and requires more time and money. Even though two gates in a GaN HEMT structure can enhance low voltage responsiveness and lower leakage currents and are frequently utilized in communication applications, their production is more complicated and comes at a higher cost and time.

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تأثير درجة الحرارة المرتفعة على الخواص الكهربائية لأجهزة GaN HEMT: مراجعة

الخلاصة: أسرع مواد أشباه الموصلات ذات النطاق العريض تطورًا مؤخرًا هي GaN، ويقدم GaN HEMT نطاقًا واسعًا من التطبيقات المحتملة في مجالات مقاومة الإشعاع والطاقة العالية ودرجة الحرارة العالية والتردد العالي. في الآونة الأخيرة، تم استخدام الترانزستورات عالية الحركة الإلكترونية القائمة على GaN (HEMT) على نطاق واسع في الصناعات الناشئة مثل تقنية G5 والمركبات الذكية الجديدة والمركبات الجوية بدون طيار والتطبيقات المختلفة بسبب قوتها العالية ومقاومتها العالية. لكن نظرًا لأن أجهزة HEMT تتمتع بكثافة طاقة عالية، فإن تأثير التسخين الذاتي سوف يتسبب في ارتفاع درجة حرارة توصيل الجهاز بشكل كبير، مما سيكون له تأثير سلبي على طول عمر الجهاز واعتماديته وأدائه. يُطلق على نوع معين من ترانزستور التأثير الميداني (FET) الذي يستخدم بنية الوصلات غير المتجانسة لتحسين الأداء اسم ترانزستور التنقل الإلكتروني العالي، أو HEMT. يقدم هذا العمل تحليلاً شاملاً لكيفية تأثير درجات الحرارة المرتفعة على الخواص الكهربائية. يتطلب فهم وتعزيز أداء أجهزة ترانزستور التنقل الإلكتروني العالي (GaN HEMT) من نيتريد الغاليوم فهمًا لكيفية تأثير درجات الحرارة المرتفعة على خصائصها الكهربائية. نظرًا للاستخدام الواسع النطاق لـ GaN HEMTs في التطبيقات الإلكترونية عالية التردد وعالية الطاقة، فمن الضروري دراسة تأثيرات درجات الحرارة المرتفعة على خصائصها الكهربائية.