

An Investigation of Thermal Reliability Issues and Solution Strategies for GaN-HEMT Power Devices

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Abstract: This paper discusses the thermal reliability design of high electron mobility transistor (HEMT) power in gallium nitride (GaN) devices in depth. GaN HEMTs' exceptional performance in high-frequency, high-voltage, and high-power applications has garnered a lot of interest. However, a major element limiting long-term stability is now their problems with thermal reliability. This paper provides a detailed analysis of the thermal challenges faced by GaN-HEMT power devices, including the self-heating effect, uneven heat distribution, thermal stress, and thermal resistance, and discusses corresponding solutions. By optimizing device structure, improving packaging technology, and enhancing thermal management measures, the thermal problems of GaN-HEMT power devices can be effectively addressed, thereby improving their thermal reliability and electrical performance. These approaches not only improve the long-term stability of the devices but also expand their potential for high-frequency, high-voltage, and high-power applications. Future research should continue focusing on innovating thermal management techniques and improving reliability models to promote the development and application of GaN-HEMT technology.

Keywords: GaN-HEMT power devices, self-heating effect, uneven heat distribution, thermal stress, thermal resistance

1. Introduction

High electron mobility transistors (HEMTs) made of gallium nitride (GaN) have become one of the indispensable core technologies in modern power electronics due to their excellent high-frequency, high-power, and high-efficiency characteristics. GaN HEMTs offer significant advantages in high-speed switching, radio-frequency applications, and high-power-density devices, and are extensively utilized in the military, communications, automobile electronics, and power electronics. With the reduction in device size and the increase in power density, the thermal reliability of GaN HEMTs has gradually become a key factor limiting their long-term stability.

The following elements have the most effects on GaN HEMTs' thermal reliability: thermal stress at the material heterojunction interface, current collapse effects, and hot carrier injection phenomena. The material heterojunction interface is prone to polarization degradation at high temperatures, leading to a decline in device performance, especially at high power densities and temperatures. The rise in temperature exacerbates the generation of interfacial traps, which in turn affect device stability. GaN HEMTs generate significant heat due to their high-power operation, and managing this heat effectively is crucial for ensuring their reliability.

Many scholars have conducted in-depth research on the thermal reliability of GaN HEMTs and proposed a series of solutions. Meneghini et al. experimentally revealed the polarization degradation mechanism of AlGaIn/GaN heterojunctions at high temperatures. They found that when the temperature exceeds 200°C, the interfacial trap density grows exponentially, leading to a 30%-60% increase in dynamic on-resistance [1]. This discovery highlights the significance of thermal control for extending device lifetime and offers an experimental foundation for a deeper understanding of the deterioration mechanism of GaN HEMTs at high temperatures. Meanwhile, Kozak et al. carried out a thorough analysis of the stability, and robustness of GaN power devices, highlighting the difficulties in managing heat in high-power, high-frequency, applications. They pointed out that thermal stresses caused by high power density and fast switching are major factors contributing to GaN HEMT degradation. Therefore, optimizing thermal design and improving material interface quality are key strategies to enhance device reliability [2]. Garg and Kale further analyzed recent developments in GaN HEMT technology, discussed thermal reliability issues, and proposed thermal design optimization schemes, such as using improved package structures to address the failure modes of high-power GaN HEMTs in high-temperature environments. They also suggested the use of heat dissipation materials and the development of GaN materials with high thermal conductivity to reduce device thermal stress [3]. Golan et al. suggested a novel GaN power FET reliability model that accounts for thermal damage and performance degradation under high-temperature operating conditions, validating the model with experimental data. This lays the groundwork for GaN power devices' thermal design and dependability under hot conditions. [4]. Amar et al. proposed a reliability-based design optimization method for GaN HEMT devices, analyzing their thermal performance in depth. They recommended fine-tuned design optimizations to improve thermal reliability, such as enhancing heat dissipation paths and selecting suitable packaging materials.[5] Meneghini et al. experimentally revealed the polarization degradation mechanism of AlGaIn/GaN heterojunctions at high temperatures and showed that the trap density at the heterojunction interface increases exponentially when the temperature exceeds 200°C, resulting in a 30%-60% increase in dynamic on-resistance, which significantly impacts GaN HEMT power performance and thermal stability.[1] Guo et al. analyzed AlGaIn/GaN HEMTs' thermal design optimization using transient simulations, showing that hot carrier effects and thermal stress are the main factors affecting thermal reliability. Their simulation model accurately predicts device thermal behavior under various operating conditions, aiding in reasonable thermal design [6]. Xu et al. suggested a reconfigured AC power cycling test platform to evaluate GaN HEMT reliability comprehensively. The platform simulates the thermal cycling process under different operating conditions, helping researchers assess the thermal reliability of GaN HEMTs during long-term operation [7]. Emon et al. reviewed the status, challenges, and solutions for GaN power modules, highlighting how the high-speed operating characteristics of GaN HEMTs exacerbate thermal management problems. They emphasized the need for more effective heat dissipation materials and packaging techniques to ensure GaN power modules remain stable under long-term, high-frequency operation [8]. Parikh et al. analyzed the commercialization requirements and successful experiences of high-quality, high-reliability 650V GaN HEMTs, emphasizing the need to solve thermal reliability issues in high-power, high-voltage applications. They pointed out that only reliable thermal design can ensure long-term, stable operation of these devices in practical applications [9].

2. Thermal Reliability Problems of GaN-HEMT

GaN-HEMT (High Electron Mobility Transistor), as a high-performance power device, has significant advantages in high-frequency, high-voltage, and high-power applications. With the device's power density steadily rising, the thermal management problem has gradually become a key factor limiting its performance and reliability. The following sections will discuss in detail GaN-

HEMT power devices' heat issues, including the self-heating effect, uneven heat distribution, thermal stresses, and thermal resistance.

2.1. Self-Heating Effect

The self-heating effect is one of the most common thermal issues in GaN-HEMT power devices. Due to the device's high power operation, the generation of Joule heat leads to a significant increase in device temperature. When the power density is high (such as 6 W/mm), high-temperature hotspots appear in the channel region below the gate, which lowers electron mobility, affecting the output power and transconductance of the device (gm). As shown in the following table, the hotspot region causes a decline in electron mobility, which further reduces output current and transconductance. The self-heating effect also leads to a decrease in frequency response. Studies have shown that increased temperature reduces the electron mobility of the channel layer, which further reduces frequency response. The self-heating effect also negatively impacts the device's high-frequency performance. The device's maximum frequency and cutoff frequency both drop as a result of the temperature rise at 40 V for the drain voltage.

2.2. Uneven Heat Distribution

Uneven heat distribution is another important thermal issue. In GaN-HEMT devices, because of the different electric field strengths in the gate and drain regions, heat is mainly concentrated below the gate and near the drain. Thermal simulations have found that placing the TSV (Through-Silicon Via) inside the active region (ISV structure) can significantly reduce the peak temperature of the channel, whereas placing the TSV outside the active region (OSV structure) is less effective. Unequal heat distribution can also lead to a decrease in the reliability of the device. During switching operations, the packaged AlGaIn/GaN HEMT device generates a high-temperature region at the multi-finger center, which increases local thermal stress and affects the long-term stability of the device.

2.3. Thermal Stress

The materials inside the device have varying coefficients of thermal expansion, which causes thermal strains. The variation between AlGaIn and GaN materials' coefficients of thermal expansion in GaN-HEMT devices leads to the production of thermal strains. Thermal stress impacts the device's electrical performance, especially at high temperatures, where it leads to a decrease in drain current and transconductance, as evidenced by an uneven distribution of the the channel's electric field. This has an impact on the device's mechanical stability and electron transport efficiency. Infrared thermography measurements of the temperature distribution in the packaged GaN devices show that high-temperature regions lead to an increase in localized thermal stresses, which in turn affects the mechanical stability of the devices.

2.4. Thermal Resistance Issues

One crucial measure of a device's thermal performance is its thermal resistance.. The thermal resistance of the packaged AlGaIn/GaN HEMT device is evaluated through thermal simulation and experimental measurements. According to the data, there is an approximate 8% discrepancy between the simulated value of 145.77 K/W and the packaged device's total thermal resistance of 134.42 K/W. The level of thermal resistance has a direct impact on the junction temperature and the reliability of the device. Further three-dimensional finite-element thermal simulations reveal that The channel temperature rises with an increase in gate finger width, which in turn raises thermal resistance.

GaN-HEMT power devices suffer from thermal problems such as the self-heating effect, uneven thermal distribution, thermal stress, and thermal resistance under high power operation. These problems not only affect the gadgets' dependability and electrical performance of the devices but also limit their potential in high-frequency, high-voltage, and high-power applications. Therefore, optimization of device structure, improvement of packaging technology, and enhancement of thermal management measures are key to improving the thermal reliability of GaN-HEMT power devices.

3. Solution Strategies for Improving Thermal Reliability of GaN-HEMTs

3.1. The Solution to the Self-Heating Effect

The DMG structure can generate an electric field gradient between the gate and the source by using two materials with different figures of merit for the gate, which can effectively control the channel's electric field distribution. The material closer to the source has a higher figure of merit, which can optimize the device's electric field distribution of the device, lower the concentration of the electric field in the hotspot area, lower the temperature rise, and effectively suppress the self-heating effect. As illustrated in Fig. 1, the study demonstrates that the device with the DMG structure has a much lower thermal resistance and a maximum temperature rise that is 11.2% lower than that of the conventional single metal gate (SMG) construction. Optimizing the geometry of the device, especially by increasing the area of the source electrode, can help disperse the heat and further reduce the self-heating effect. Increasing the area of the source electrode can enhance heat diffusion, enabling the heat to be distributed more efficiently dispersed inside the device to reduce hotspots and lower the temperature. The optimized layout of the TSV (Through-Silicon Via) is also an effective cooling measure. Placing the TSV in the active region (ISV structure) significantly reduces the peak temperature of the channel, as the heat can be transferred more directly through the TSV to the external cooling system, further improving the cooling effect.

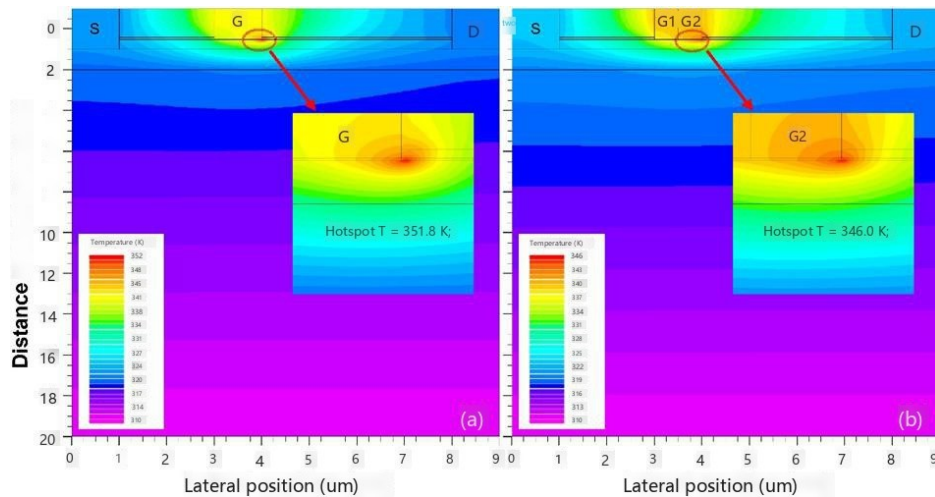


Figure 1: Temperature profiles of AlGaIn/GaN HEMT devices with power density of $P = 6 \text{ W/mm}$, (a) SMG structure, (b) DMG structure. [10]

3.2. The Solution to Uneven Heat Distribution

During device operation, heat is mainly concentrated in the lower gate and drain regions, and the generation of such localized hotspots not only affects the performance of the device but may also lead to device failure. To solve this problem, a source-bridged field plate (SBFP) structure is proposed, which optimizes heat distribution by changing the geometry of the field plate. The SBFP structure

redistributes the electric field in the channel layer to reduce the temperature, especially at the gate edge and drain region. It has been shown that the SBFP structure moves the hotspot from the edge of the drain side of the gate to the foot of the SBFP, significantly reducing the maximum temperature. As shown in Fig. 2, optimizing the placement of the TSVs can also effectively improve heat distribution. Placing the TSVs in the active region (ISV structure) results in a more uniform heat distribution and effectively prevents the formation of hotspots. By optimizing the TSV layout, heat can be more efficiently transferred from the high-temperature region to the cooling system to reduce the peak temperature of the channel. Optimizing the device geometry and improving the layout of the heat path can greatly improve the heat distribution of the device to avoid localized overheating.

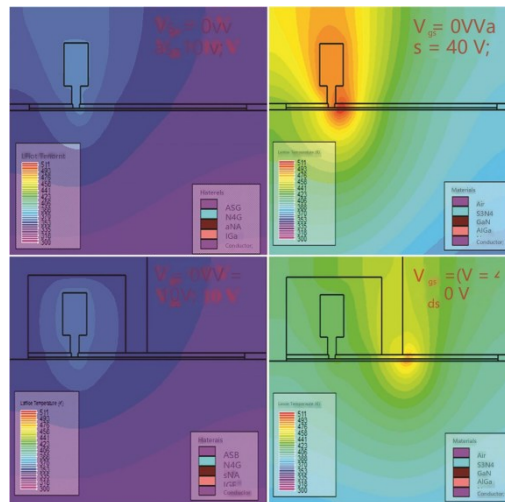


Figure 2: Dot temperature of t-gate and SBFP structure. The distance between the drain side t-gate head and the SBFP is $0.9 \mu\text{m}$. The SBFP structure has a lower maximum temperature than the t-gate structure. [11]

3.3. Solutions for Thermal Stresses

Thermal stresses are mainly due to the different coefficients of thermal expansion of different materials, and the difference in thermal expansion between AlGaIn and GaN in GaN-HEMT devices can lead to thermal stresses, which in turn affect the performance and mechanical stability of the devices. To solve the thermal stress problem, the device structure can be optimized to reduce thermal stress. The use of a bimetallic gate structure (DMG) can effectively improve the electric field distribution in the channel to reduce the peak electric field under the gate, reduce the stress concentration caused by the difference in thermal expansion, and thus reduce the generation of thermal stress. Studies have shown that after the use of the DMG structure, the thermal stress of the device has been significantly reduced, especially at the edge of the drain gate. The electric field distribution has been optimized, and the generation of thermal stress has been effectively suppressed, as shown in Fig. 3. As shown in Fig. 3, the optimized thermal field distribution can effectively alleviate the stress difference between materials, and the gate finger width of the device also has an important effect on the distribution of thermal stress. By controlling the gate finger width, the temperature distribution in the channel can be adjusted to affect the generation of thermal stress. At the same thermal power density, the larger the gate finger width, the higher the channel temperature and the higher the thermal stress. Therefore, by optimizing the gate finger width and structural design, thermal stress can be further reduced. Improving the packaging technology can also effectively reduce thermal stress, and the use of better thermal conductivity substrate materials, such as diamond,

significantly enhances thermal conduction efficiency to reduce the temperature gradient inside the device and thus reduce thermal stress.

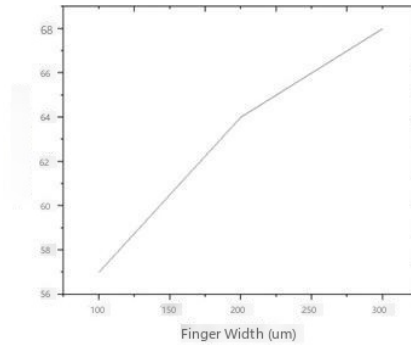


Figure 3: Simulated gate finger vs. finger width peak temperatures in the same type of structure. [12]

3.4. The Solution to the Thermal Resistance Problem

One of the main elements influencing the GaN-HEMT devices' thermal performance is thermal resistance. When thermal resistance is high, heat cannot be dissipated efficiently, leading to an increase in the junction temperature of the device. This, in turn, affects the device's performance and reliability. To address the thermal resistance problem, the thermal conduction path can be improved by optimizing the device structure. The use of a bimetallic gate structure (DMG) can significantly reduce thermal resistance because the DMG structure optimizes the electric field distribution, allowing heat to be more evenly distributed and preventing local overheating. Additionally, optimizing the selection of packaging materials is an effective means of reducing thermal resistance.

The use of high thermal conductivity encapsulation materials, such as diamond, significantly improves thermal conductivity and reduces thermal resistance. Diamond has an exceptionally high thermal conductivity, which greatly enhances the thermal performance of the device and improves its thermal reliability. As shown in Figure 4, when GaN-HEMT devices are encapsulated with diamond, the thermal resistance is greatly reduced compared to traditional encapsulation methods, resulting in significantly improved thermal effects. By optimizing the device structure and improving packaging technology, thermal resistance can be effectively reduced, enhancing the heat dissipation capability and overall stability of the device.

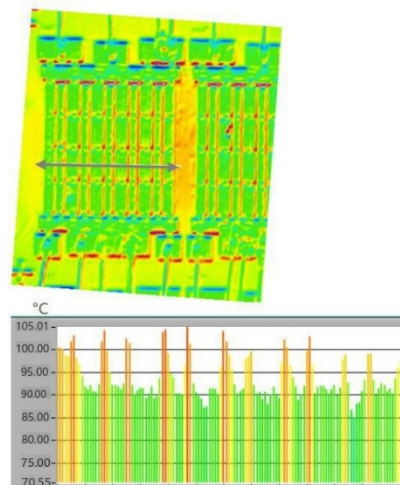


Figure 4: Temperature distribution and line distribution across the center polyfinger of the encapsulated GaN-HEMT. [13]

3.5. Integrated Optimization Methods

The comprehensive optimization method can significantly improve the thermal reliability of GaN-HEMT devices by combining various techniques. The bimetallic gate structure (DMG) and diamond packaging technology effectively reduce hotspot temperature and thermal resistance. The DMG structure reduces self-heating effects and thermal stresses by regulating the channel's electric field distribution, while the diamond package enhances the thermal performance of the device by providing higher thermal conductivity. With this combination of structural and packaging optimizations, the device's total thermal performance is significantly improved. The use of high thermal conductivity materials, such as graphene channel materials, can also improve thermal conduction. Graphene, being highly thermally conductive, offers significant advantages in thermal management, effectively reducing the device temperature and improving thermal reliability. Through these comprehensive optimization measures, heat can be more effectively dissipated from the device, improving its thermal stability and long-term reliability. The integrated optimization method not only improves the thermal performance of the device but also ensures the stable operation of GaN-HEMT devices under harsh conditions, including high power, high frequency, and high voltage applications.

4. Conclusions

GaN-HEMT power devices perform well in high-frequency, high-voltage, and high-power applications, but their thermal reliability issues remain a key factor limiting long-term stability. This paper proposes various solutions to address thermal problems such as the self-heating effect, uneven heat distribution, thermal stress, and thermal resistance. The self-heating effect can be significantly mitigated using the bimetallic gate structure (DMG), which reduces the maximum temperature rise by 11.2% compared to the single-metal gate structure (SMG). Additionally, optimizing the geometry (e.g., increasing the source area) and adopting the active area TSV (ISV) layout can effectively reduce the channel's peak temperature. The problem of uneven thermal distribution can be optimized using the source-bridged field plate structure (SBFP), which shifts the hotspot from the drain-side gate edge to the footer. When combined with the optimized TSV layout, this structure further improves thermal distribution. The thermal stress problem can be significantly mitigated by optimizing the device structure (e.g., DMG) and improving packaging technology (e.g., using a diamond substrate). Thermal resistance is effectively reduced through the DMG structure and efficient packaging materials (e.g., diamond encapsulation). The combined optimization of device structure, packaging technology, and thermal management measures (e.g., the use of graphene channels and highly efficient heat dissipation materials) can significantly improve the thermal reliability and electrical performance of the devices. This not only enhances their long-term stability but also expands their potential in high-frequency, high-voltage, and high-power applications. Future research should focus on innovations in thermal management technology and improvements in reliability models to promote the further development and application of GaN-HEMT technology.

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