Reliability issues of GaN HEMT: Current status and challenges

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Abstract. With the development of power electronic devices, there is an increasing demand for energy-saving, emission reduction, and environmental protection. Thus, higher energy conversion efficiency of power electronic devices is required. While traditional Si-based power electronic devices have the disadvantage of low energy utilization efficiency and high thermal losses, GaN-based HEMT has significant advantages, making it a frontier and hotspot in global semiconductor research. However, the failure mechanisms that affect the reliability of GaN HEMTs are not completely comprehended. Many reliability issues affect devices' performance, among which electrical reliability and thermal reliability are widely studied concerns. Electrical reliability issues contain inverse piezoelectric effect, hot electron effect, trapping effect, and mental instability. Thermal reliability issues contain self-heating effects, which are caused by the material's unsatisfying thermal conductivity, and improper structure design. This paper is focused on the current research results of the GaN HEMT's electrical reliability and thermal reliability. The first part of this paper gives a review of GaN HEMT reliability issues at their current status, and the second part outlines the challenges of GaN HEMTs in future development. This review will help researchers to better understand factors that affect GaN HEMT's reliability and help with their device design for further research.

Keywords: gallium nitride, HEMTs, reliability, challenge.

1. Introduction

Gallium Nitride (GaN) is a new generation of semiconductor materials after silicon and gallium arsenide materials. GaN-based electronic devices are more suitable to work under high-temperature, high-power, and high-frequency conditions than silicon-based and GaAs-based electronic devices because their band gap, breakdown field, electron mobility, and thermal conductivity are higher, while the dielectric constant is relatively low (shown in Table 1) [1].

Table 1. Physical characteristics of three semiconductor materials [2].

	Breakdown electric field($MV\cdot cm^{-1}$)	Band gap (eV)	Electron mobility ($cm^2\cdot V^{-1}\cdot s^{-1}$)	Thermal conductivity ($W\cdot mK^{-1}$)	Dielectric constant
GaN	3.0	3.49	2200	>150	9.0
Si	0.3	1.10	1350	150	11.8
GaAs	0.4	1.42	8500	50	12.8

However, GaN-based devices' reliability problems are not solved, making it hard to carry out large-scale commercial applications. Thus, solving the reliability issues of GaN HEMTs is of great significance. Reliability issues contain things like (1) Power density and efficiency: GaN HEMT has higher power density and higher efficiency than traditional Si devices. Therefore, it is necessary to consider its stability at high power and long-term reliability. (2) Leakage current and breakdown voltage: Leakage current refers to the current level when the device is turned off and is important for stability and reliability. The breakdown voltage refers to the maximum allowable voltage within the normal operating range, which is also very important to protect the device from destruction. (3) Time Domain Response: The time domain response of GaN HEMT refers to the speed at which the device switches slowly. From a reliability perspective, the balance between switching speed and device reliability needs to be considered to ensure that the device is not damaged by excessive switching speeds. (4) Temperature: High-power and high-frequency situations can cause GaN HEMT to operate at elevated temperatures, so device stability and long-term reliability at high temperatures need to be concerned. (5) Mechanical and thermal stress: In packaging and thermal systems, GaN HEMTs are subjected to mechanical and thermal stress, which affects device reliability. Many researchers are studying GaN HEMTs' reliability issues and they have achieved some progress. But the internal defects of the GaN material are very complex, there are still many unsolved problems. This paper concludes and evaluates the current research results of GaN HEMTs' reliability issues and discusses some challenging reliability problems.

2. Reliability issues

While GaN HEMTs have exceptional properties when facing high power densities, the unique characteristics of GaN and 2DEG also present them with some special reliability challenges. The reliability of GaN HEMTs includes many aspects. This chapter mainly focuses on electrical reliability and thermal reliability.

2.1. Electrical reliability issues

The overall performance of GaN-based HEMT, especially the electrical reliability, is seriously limited by problems such as large gate leakage current, GaN Oxidation, and trapping effects. This chapter chooses some typical problems to introduce.

2.1.1. Current collapse. Current collapse is a phenomenon where the device experiences a sudden decrease in current flow under certain operating conditions (see Figure 1). In 1994, current collapse was first found in GaN HEMTs by M. A. Khan et al [3] and was restored by illumination at a wavelength of 600 nm, indicating that the current collapse is associated with hot electron-generated defects. In 1999, Klein et al [4] studied the connection between current collapse and wavelength and found that the trap state in bandgap at a certain energy level is an important cause of the collapse of the GaN HEMT current. In 2001, R. Vetury et al [5] created the virtual gate model and suggested that captured electrons at the surface of AlGaN form a virtual gate due to the high-field effect, which leads to current collapse. The virtual gate phenomenon can be prevented using passivate. In 2003, Takashi Mizutani et al [6] tried injecting electrons from the gate. The findings imply that the collapse occurred because of the electron-capturing effect of the electronic state between the surface of the gate and the drain. They also reported that passivating the device surface can reduce current collapse phenomena. In 2010, 2D physical simulations were used to analyze the effects of current collapse. The findings indicated that the current collapse was related to two trap levels and surface traps [7]. In 2018, it was discovered that threading dislocations played a significant role in the GaN HEMTs' current collapse effect. The temporary electrical charge stored in the AlGaN layer is proven to cause the current collapse [8].

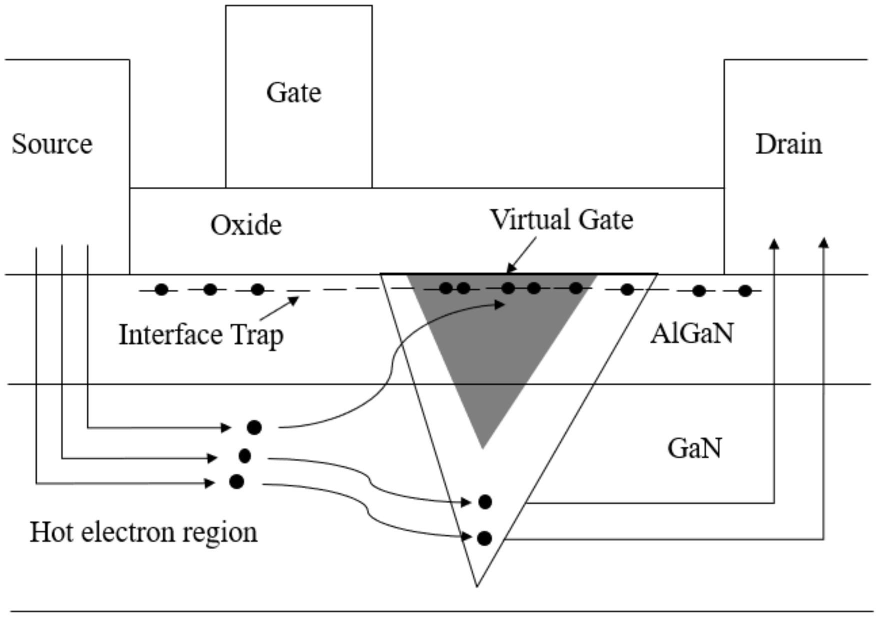

Figure l. A scheme of the current collapse mechanism [9].

2.1.2. Electrochemical GaN oxidation. When the GaN surface is subjected to specific conditions such as high temperature, moisture, and device current, oxygen can react with it, which results in erosion at the place near gate edges. As a consequence, the parasitic resistance increases, and transconductance decreases, leading to a reduction in the device's performance [10].

The gate will be structurally damaged as a result of the electrochemical dissolution of GaN after long operation. Electrochemical dissolution is associated with water vapor. F. Gao et al [11] showed that water from the environment and the surface of the passivation layer is an important reason for the formation of surface pits. Oxygen is another factor associated with electrochemical dissolution. P. G. Whiting et al [12] made EDS/EELS analyses via STEM and GRTEM. The results showed that the interfacial defect is caused by the formation of an amorphous AlO layer.

2.1.3. Inverse piezoelectric effect. When subjected to high voltage, AlGaN/GaN experiences stress and strain due to its piezoelectric nature, which can result in the formation of lattice defects or even cracks. These cracks and defects can result in parasitic resistance and increased gate leakage current [13]. The degradation degree is related to temperature. Low temperatures can alleviate the inverse piezoelectric effect and reduce unalterable degradation, but more severe reductions in drain current and maximum transconductance are likely to occur [14]. J.A. del Alamo et al [15] discovered that high electric fields create mechanical stress in the AlGaN layer, resulting in increased elastic energy. This can lead to the formation of electrically active lattice defects, which can cause gate leakage current and electron trapping effects. According to this mechanism, the characteristics of the AlGaN layer, such as thickness and composition, are factors that affect device reliability as they change the initial elastic energy level in the AlGaN. Also, optimizing device structures can prevent high electric fields, thus enhancing GaN HEMT's reliability. Figure 2 shows the stress situation of GaN HEMT under high VDG. The vertical arrow represents a high field generated under the gate. Horizontal arrows represent the mechanical stress formed in the same region.

DOI: 10.54254/2755-2721/23/20230661

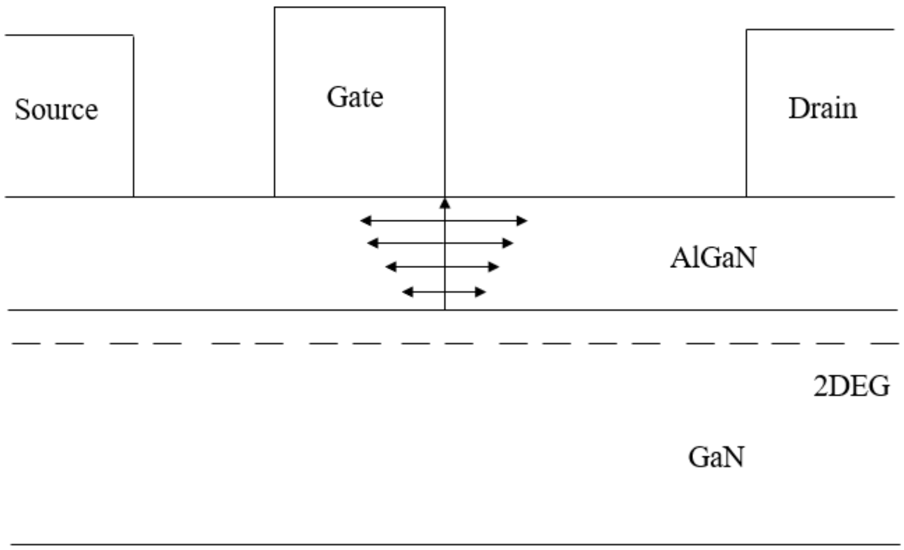

Figure 2. A graphical illustration of GaN HEMT under high VDG [15].

2.2. Thermal reliability issues

Although AlGaN/GaN HEMTs have exceptional performance in high-power, high-frequency phenomena for their unique characteristics, careful thermal management is needed to ensure the device's efficiency and stability. For instance, a hot spot may form on the gate region in the heating process, which can significantly affect the heat distribution of the device and cause structural damage to devices [16]. Thus, the thermal design of GaN HEMTs needs to be seriously taken into account. This chapter first introduces the simulation of the thermal properties, then some improving methods are discussed.

2.2.1. Numerical simulation. Considering that GaN-based HEMTs have substantial applications in high-power systems and power devices, the devices need to handle large power densities. The power dissipated in GaN devices under such circumstances can lead to significant self-heating effects, drastically affecting the devices' electrical characteristics. Therefore, a precise simulation of the thermal distribution in GaN HEMTs and modification of the device structure through simulations are important [17].

In 2001, L.F. Eastman et al [18] applied nonlinear 3D heat spreading simulations to investigate how the maximum channel temperature varies based on the layout geometry and the amount of normalized heat power dissipated. In 2009, F. Bertoluzza et al [19] made a simulation on GaN HEMTs with different geometry, substrate material, passivation, and cooling strategy. It is reported that three-dimensional effects may have a significant effect on the prediction's reliability. In 2010, Douglas et al [20] noticed a significant difference in the predicted highest temperature between 2D and 3D simulations, which validates the importance of conducting 3D analyses to enhance the precision and dependability of simulation.

In the case of multi-finger devices, the thermal coupling relies significantly on the device's structure. Symmetric structures can affect cooling conditions, rendering them unsuitable for thermal analysis in practical situations. Thus, it is crucial to comprehend how different structures of multi-finger devices affect thermal distribution. To achieve this goal, Z. Liao et al [16] created a precise 2D finite-element model based on scanning electron microscopy data that matches the dimensions of the actual device. The research takes into account and carefully evaluates the device's structural factors such as gate length, GaN layer thickness, and substrate thickness.

2.2.2. Improving methods. Thermal properties are strongly related to the substrate materials that HEMT devices use. Since diamond is a material with high thermal conductivity, it can be a suitable substrate used to reduce the self-heating effect. T. Liu et al [21] tried integrating diamond substrates with GaN HEMTs to improve heat dissipation and thermal reliability. The direct current characteristics demonstrate a decrease in the self-heating effect, as the device's maximum current density rises, while the peak junction temperature decreases.

The thermal conductivity of AlGaN barrier layers is another factor that affects thermal reliability. Wang et al [22] introduced another layer to the buffer layer, called the back-barrier layer. Its thickness created a thermal barrier layer that impacted the device's reduction in thermally induced current during high-power operation. This method not only enhanced the thermal performance but also increased the device's withstand voltage, which resulted in a decrease in the current collapse effect.

3. Challenges for GaN HEMTs

In recent years, GaN HEMT technology is quickly developing, during which many challenges have shown up, waiting for designers to solve. Herein, challenges are divided into electrical-related and thermal-related problems.

3.1. Electrical-related challenges

GaN HEMT electrical reliability problems are related to many aspects, such as working conditions and structural materials. Under different situations, GaN HEMT has varied electrical stability, making it hard to reach theoretically predicted high performance in real-world applications. Some specific challenges in electrical reliability are listed below.

Trapping effects during the operation of AlGaN/GaN HEMTs are significant obstacles that cause performance degradation, such as reduction in transconductance, output power, and drain and gate lag [23].

In terms of material problems, GaN devices are likely to suffer from electrochemical oxidation in long-term use. Metal can react with water and oxygen, which leads to interfacial defects. The piezoelectric nature of GaN can result in parasitic resistance and increased gate leakage current, negatively affecting its electrical reliability. For future development, researchers need to reduce the negative effects that internal defect of materials brings about.

3.2. Thermal-related challenges

As for thermal reliability issues, careful device thermal management is crucial for producing reliable and robust GaN HEMTs. Ahead of improving the thermal design, precise numerical simulations of the device’s thermal characteristics are required to study the underlying thermal transport mechanisms. However, simulating the thermal distribution of GaN HEMTs with high accuracy is a challenging task. This is because accurately modeling the structures requires considering the various nature of materials and trapping effects on bulk and surface [19]. Apart from challenges in simulation, the structure material also faces challenges. The material of extrinsic substrates is essential for devices’ thermal characteristics. Normally, materials with higher thermal conductivity are preferred. However, some high thermal conductivity materials may be incompatible with other substrate materials. For example, diamond, known as a high thermal conductivity material, is not a satisfying option because of the GaN-diamond lattice mismatch [24]. Further investigation is needed to solve those challenges.

4. Conclusion

This paper reviewed the reliability issues of GaN HEMTs. The factors that cause the decrease in devices’ performance include the electric field, temperature, and material characteristics. Electric field distribution can be controlled effectively by surface passivation, gate structure modification, and a barrier layer. By optimizing the process of the device, its robustness against the oxidation mechanism can be significantly improved. By improving the device’s thermal characteristics, crystal damage related to thermal mechanical stress can be prevented.

The performance that GaN HEMT shows up in the real world is much lower than its theoretical performance. Once the reliability problems of GaN HEMT are solved, its performance has the potential to rise largely. But for the foreseeable future, GaN HEMT reliability issues will remain a limiting factor that needs further study to overcome.

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DOI: 10.54254/2755-2721/23/20230661

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