



Effect of Structural Layer on GaN HEMT Device Performance

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Abstract. Semiconductor materials have special conductive properties and are widely used in integrated circuits, transistors, optoelectronic devices and other fields. GaN, as one of its representative materials, has made significant progress in material growth and process preparation at present. However, the trap effect caused by structural layer defects during the device fabrication process will affect the performance of the device. This paper first discusses the locations and causes of surface states, interface defects of AlGaIn/GaN heterojunctions, and bulk defects. Then, by analyzing existing research results, it elaborates on the impacts of these defects on device performance. Finally, it introduces measures such as GaN cap layers, passivation layers, and field plate structures that can improve defect-related issues and effectively reduce the negative effects of defects on device performance. This study provides a relatively comprehensive introduction to the defects of GaN HEMT and their impacts, and offers ideas for its future technological breakthroughs.

Keywords: Semiconductor, GaN HEMT, Device Defects.

1 Introduction

Semiconductor materials hold a pivotal position in modern science and technology as well as industry, and are constantly being applied in fields such as integrated circuits, optoelectronic devices, communication equipment, and medical devices. With the progress of technology and the ever-growing demand for electronic devices with higher performance, the semiconductor materials industry has sustained a continuous and rapid pace of development. The performance bottlenecks of the first and second generation semiconductor materials, as well as the impetus from emerging application demands such as 5G, have led to the emergence of the third generation semiconductor materials. Gallium nitride (GaN), as a representative of the third-generation wide bandgap semiconductor materials, has emerged as a core material for high-frequency, high-power, and high-temperature electronic devices due to its high breakdown field strength, high electron mobility, excellent thermal stability, and direct bandgap property. In recent years, significant progress has been made in the research on GaN structures. For instance, in the field of epitaxial growth, the team from Peking University, using the STEM-EELS technique, was the first to achieve atomic-scale visualization of the prism-shaped stacking fault (PSF) in GaN [1]. This revealed the changes in phonon

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modes caused by defects and their modulation laws on thermal conductivity, providing a new idea for defect-based thermal management. The Xiu Xiangqian team of Nanjing University optimized the HVPE growth parameters through numerical simulation, and realized a GaN thick film with 8% uniformity and 200 $\mu\text{m}/\text{h}$ growth rate on a 6-inch SiC substrate, and the dislocation density was reduced by 30% compared with the traditional process [2]. However, these studies lack a comprehensive review of the impact of different structural defects and the reasons for the impact.

By analyzing and summarizing the existing research on the effects of defects in GaN HEMT devices, this paper systematically reviews the formation mechanism of AlGaIn surface state, interface defects and bulk defects in AlGaIn/GaN heterojunction, and the effects of defects at different positions on device performance. In addition, effective measures to construct GaN cap layer, passivation layer and field plate structure are summarized for how to improve the related problems of defects. This paper aims to provide scholars with systematic knowledge of defect-related issues through literature research, data analysis and induction, and provide ideas for how to reduce the impact of defects and improve device performance.

2 Location and causes of different defects in AlGaIn/GaN HEMT

2.1 Location of defects

Fig 1 illustrates the GaN HEMT device structure and its major defect locations. According to the vertical direction of the device, from top to bottom are the surface states located on the AlGaIn surface, the bulk defects in the AlGaIn barrier layer, the interface defects at the AlGaIn/GaN heterojunction interface, the bulk defects in the GaN buffer layer and the channel layer.

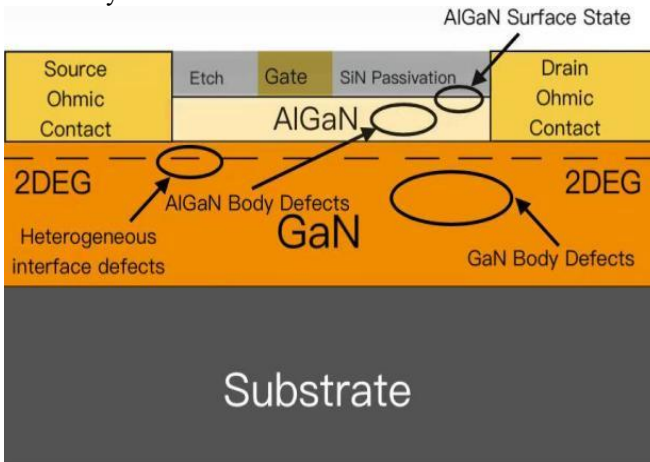


Fig. 1. Schematic representation of defect locations in AlGaIn/GaN HEMT devices

2.2 The cause of the AlGa_N surface state

When a piece of semiconductor is suddenly interrupted, the periodic lattice of the surface ideal is interrupted, resulting in the appearance of electronic states (energy levels) in the band gap, which are called surface states [3]. There are three main reasons for the formation of AlGa_N surface states. First, the polarization field terminates on the AlGa_N surface, resulting in the bending of the surface energy band and the formation of unsaturated hanging bonds [4]. Secondly, the adsorbed molecules on the AlGa_N surface affect the surface states through the dynamic mixing mechanism [5]. Third, in the device preparation process, etching, oxidation and other processes will cause lattice defects or introduce impurities on the AlGa_N surface and destroy the surface atomic arrangement.

2.3 Causes of interface defects in AlGa_N/GaN heterojunctions

Wurtzite nitrides have special low symmetry, which results in spontaneous polarization, while there is lattice mismatch between AlGa_N and GaN, which causes piezoelectric polarization [6]. The superposition of the two polarizations leads to the formation of a strong polarized electric field at the interface, which attracts charge aggregation and induces interfacial state defects. Moreover, the lattice mismatch between AlGa_N and GaN leads to the complete saturation of interface atoms, and the formation of hanging bonds is also one of the reasons for the interface defects of heterojunction. In addition, operations such as etching and oxidation inevitably destroy the stability of chemical bonds and introduce damage during device preparation.

2.4 Causes of bulk defects

The bulk defects mainly include GaN buffer layer defects, GaN channel layer defects and AlGa_N barrier layer defects. There are several reasons that lead to the generation of these three kinds of defects in the device manufacturing process. Firstly, the most suitable substrate material for GaN HEMT is GaN. However, due to its high cost and small size, many manufacturers choose to use heteroepitaxial substrates [7], which can lead to lattice mismatch and other issues, introducing dislocations and defects during the material growth process. Secondly, since the GaN buffer layer must meet the high-resistance characteristic, impurities are often introduced during the process of achieving this requirement, thereby forming bulk defects. For instance, by doping Fe impurities, the background carrier concentration is supplemented to a certain extent, thus achieving the high-resistance characteristic required by the device structure for the GaN buffer layer [8].

3 Effect of defects on device performance

3.1 Surface state

Surface states have the functions of band modulation, carrier trapping and interface reaction, which significantly affect the device performance. Pit defect on the AlGa_N surface is one of the most important surface states. Due to the fact that the pit-like defects on the surface of AlGa_N can trap electrons and form virtual gates, it directly leads to the gate delay current collapse effect and an increase in the source-drain resistance. In addition, the degree of influence on device performance is positively correlated with the number of surface pothole, while the leakage delay test shows that the AlGa_N surface pothole defects have little effect on the leakage delay current collapse [9]. Therefore, surface states can lead to negative effects such as deterioration of device performance at high frequency, conduction loss and efficiency decline.

3.2 Interface defects in AlGa_N/Ga_N heterojunctions

The heterojunction interface is the key area of contact between the two materials, which has the core role of polarization effect and the formation of two-dimensional electron gas. When the device operates in high drain voltage or high carrier density, high energy hot carriers can depassivate or reconfigure the defects near the AlGa_N/Ga_N interface [10]. This leads to significant reduction of drain current and transconductance, offset of threshold voltage and other issues, which makes the DC and RF performance.

Interface defects can be introduced by oxidation operation. Therefore, the interface defect environment of heterojunction can be simulated by changing the number of adsorbed oxygen molecules at the interface through simulation software, and then the effect on device performance can be observed according to the simulation results. According to the resonance absorption peak characteristics of oxygen molecules, the amount of oxygen molecules at the interface of AlGa_N/Ga_N heterojunction can be changed by irradiating the surface of AlGa_N/Ga_N heterojunction with a wavelength of 760nm. The results show that the reduction of oxygen molecule content at the interface of the heterojunction will lead to the decrease of two-dimensional electron gas concentration [5], which will reduce the cut-off frequency of the device and lead to the deterioration of the high-frequency performance of the device. In addition, studies have shown that the defect at the interface of the heterojunction is related to the electron density, and the defect density is positively correlated with its influence degree [11].

3.3 Bulk defect

Although the carrier transport process of Ga_N HEMT device is independent of AlGa_N barrier layer, the barrier layer, as a key carrier for the realization of device function, is closely related to the formation of two-dimensional electron gas, and the defects in it will also affect the performance of the device to a certain extent. The buffer layer of Ga_N is the key structure connecting the substrate and the AlGa_N barrier layer, which

has the important function of alleviating the lattice mismatch effect and thermal conductivity mismatch effect, and improving the long-term reliability of the device [12]. The structure of the GaN channel layer can transport two-dimensional electron gas, and the defects here directly affect the DC performance of the device.

Bulk defects can lead to gate hysteresis [13], which directly affects the switching period and introduces phase delay, thus seriously damaging the RF characteristics and long-term reliability of the device. The GaN buffer layer is very closely related to the channel layer. After electrons are captured by the buffer layer defects, the resistance of the channel layer increases and the device performance is reduced. Under the leakage delay test, the more defects in the buffer layer, the more serious the current collapse caused [9].

4 Improvement measures

4.1 GaN cap layer

GaN cap layer generally refers to a functional layer covering the interface of heterogeneous junctions. By introducing specific structures or materials (such as P-type GaN cap layer), functions such as regulating the concentration of two-dimensional electron gas carriers can be realized, and the channel electrons can be isolated from the device surface, thereby reducing the impact of device defects on performance. GaN cap layer plays a significant role in improving the current collapse effect. Experiments show that in a certain range, with the increase of cap layer thickness (0-10nm), the improvement effect is better [14].

In addition, the intrinsic GaN cap layer can also improve the device performance. Different from the commonly used cap layer, this cap layer does not require doping, but uses the etching process to form a specific shape. The intrinsic cap layer can reduce the concentration of two-dimensional electron gas in the channel, the peak electric field at the gate edge, and form a new electric field peak at the edge of the device leakage electrode, thereby increasing the breakdown voltage and making the device more stable [15].

4.2 Passivation layer

The essence of passivation is to form a protective layer on the device surface through the deposition of a dielectric film, which can suppress the current collapse and improve the DC performance of the device. Usually surface passivation materials are SiNX, SiO₂ and so on. Passivation can be performed by plasma chemical vapor deposition (PECVD) or low pressure chemical vapor deposition (LPCVD). In recent years, with the continuous exploration of researchers, the choice of materials and methods for surface passivation process has become more and more abundant. Some studies have shown that the passivation of SiNO material can increase the drain output current and transconductance, which also has great potential in other fields [16]. A new passivation method of silicon nitriding deposited by magnetron sputtering [17], compared with the

traditional PECVD-SiN passivation, increases the conduction current by 20%, and has a good development prospect. In addition, the thermal atomic layer deposition method also performs well, and the use of aluminum oxide as passivation material can better improve the device performance compared with the traditional passivation method [18].

4.3 Field plate structure

The field plate structure can adjust the leakage power field, so as to suppress the current collapse and improve the device operating frequency. The field plate structure can be divided into single-layer field plate, multi-layer stepped field plate, floating composite field plate and Γ type grid field plate. By adding the gate field plate structure, the parasitic capacitance and gate resistance are smaller and the output power is increased [19]. The field-plate structure can also improve the breakdown voltage. Researchers have achieved a record 1380 V breakdown voltage of AlGaIn/GaN HEMT with a maximum field distribution of 3.7 MV/cm in simulation experiments, and longer source field-plate devices have better performance than shorter devices [20].

5 Conclusion

GaN HEMT devices play an important role in many fields, but the defects formed in the manufacturing process always hinder their core performance such as output power and cut-off frequency. This paper reviews several major defects of GaN HEMT devices, combines the main causes and effects of several defects, and summarizes three commonly used methods to improve defects and improve device performance by introducing cap layer, a passivation layer and a field plate structure. At present, there is still much room for progress on how to reduce the impact of defects on the performance of GaN HEMT devices. Comparing the causes of different defects and analyzing their effects can provide researchers with some ideas on how to improve the performance of devices. In terms of material selection, it is necessary to find new and more suitable materials as substrates. In terms of material structure, a new structure is tried to improve the lattice matching degree and reduce the voltage polarization. In terms of material growth, optimizing growth conditions can reduce dislocation and defect density. In terms of manufacturing process, new production processes are being tried to improve lattice damage and defects introduced by process steps. By reducing defects and improving the related problems caused by them, GaN HEMT devices can achieve better performance in the future electronics industry. Due to its characteristics of meeting the high frequency band requirements of inter-satellite links and supporting the miniaturization of Massive MIMO antenna arrays, it will dominate the Leo satellite communication and base station RF front-end in the future, achieve breakthroughs in the field of chemical energy storage, and affect the new energy automobile industry.

References

1. H. Jiang, T. Wang, Z. Zhang et al., Atomic-scale visualization of defect-induced localized vibrations in GaN. *Nat. Commun.* 15, 9052 (2024)
2. W. L. Xu, Y. H. Gan, Y. W. Li et al., High rate HVPE growth of high uniformity 6-inch GaN thick film. *J. Synth. Cryst.* 54(1), 11-16 (2025)
3. X. X. Chang, J. L. Gong, On the importance of surface reactions on semiconductor photocatalysts for solar water splitting. *Acta Phys.-Chim. Sin.* 32(1), 2-13 (2016)
4. F. Xie, D. C. Li, The influence of surface states on two-dimensional electron gas in AlGaIn/GaN heterostructures. *Electron. Technol.* 22(3), 78-80 (2009)
5. Y. Ma, Research on surface dynamic doping effects of AlGaIn/GaN heterojunctions. M.S. thesis, Univ. Sci. Technol. China (2023)
6. Y. L. Gao et al., Electronic structure of GaN surfaces. *J. Phys.: Condens. Matter* 33, 035002 (2021)
7. M. Alomari, GaN HEMT: Substrate challenges. *Compd. Semicond.* 1, 30-33 (2018).
8. K. Wang, Y. H. Xing, J. Han et al., Growths of Fe-doped GaN high-resistivity buffer layers for AlGaIn/GaN high electron mobility transistor devices. *Acta Phys. Sin.* 65(1), 016802 (2016)
9. G. Y. Xi, F. Ren, Z. B. Hao et al., Influence of pit defects on AlGaIn surface and dislocation defects in GaN buffer layer on current collapse of AlGaIn/GaN HEMTs. *Acta Phys. Sin.* 57(11), 7238-7243 (2008)
10. S. T. Pantelides, Y. Puzyrev, X. Shen et al., Reliability of III-V devices-the defects that cause the trouble. *Microelectron. Eng.* 90, 3-8 (2011)
11. J. Guan, Y. Wang, L. Huang et al., Effect of defects on the C-V characteristics for AlGaIn/GaN MIS-HEMTs based on 2D simulations. In: *Proc. IEEE EICT*, Shenzhen, 71-74 (2024)
12. K. Ghosh, S. Das, S. Ganguly et al., Impact of GaN buffer layer thickness on structural and optical properties of AlGaIn/GaN based high electron mobility transistor structure grown on Si(111) substrate by plasma assisted molecular beam epitaxy technique. In: *Proc. IEEE C3IT*, Hooghly, 1-4 (2015)
13. N. Braga, R. Mickevicius, M. Shur et al., Simulation of gate lag and current collapse in GaN heterojunction field effect transistors. In: *Proc. IEEE CSIC Symp.*, Monterey, 287-290 (2004)
14. S. Yoshida, Y. Sakaida, J. T. Asubar et al., Current collapse in AlGaIn/GaN HEMTs with a GaN cap layer. In: *Proc. IEEE IMFEDK*, Kyoto, 48-49 (2015)
15. G. H. J., D. B. X., Y. Song et al., Characteristic analysis of new AlGaIn/GaN high electron mobility transistor with a partial GaN cap layer. *Acta Phys. Sin.* 66(16), 167301 (2017)
16. K. Y. Cheng, S. C. Wu, C. J. Yu et al., Comparative study on performance of AlGaIn/GaN MS-HEMTs with SiNx, SiOx, and SiNO surface passivation. *Solid-State Electron.* 170, 107824 (2020)
17. C. Yu, G. J. Ding, Q. Feng et al., An AlGaIn/GaN HEMT with sputter-SiN passivation for the on-state performance improvement. *Micro Nanostruct.* 168, 207316 (2022)
18. T. N. T. Do et al., Effects of surface passivation and deposition methods on the noise performance of AlInN/AlN/GaN high electron mobility transistors. *IEEE Electron Device Lett.* 36(4), 315-317 (2015)
19. A. Toprak, M. T. Haliloğlu, Y. Durmuş et al., Effect of gate field plate and Γ (gamma)-gate structures on RF power performance of AlGaIn/GaN HEMTs. In: *Proc. IEEE EuMIC*, Paris, 215-218 (2015)

20. D. Godfrey et al., Investigation of AlGaIn/GaN HEMT breakdown analysis with source field plate length for high power applications. In: Proc. IEEE ICDCS, Coimbatore, 244-246 (2020)

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