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Investigation of Hot Carrier Injection Effects in Recessed-Gate GaN MIS-HEMTs by TCAD Simulations

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Abstract

This study focuses on the advantages of recessed gate GaN High Electron Mobility Transistors (MIS-HEMTs) and the reliability issues. GaN MIS-HEMTs have been widely applied in high-power and high-frequency fields. However, the Hot Carrier Injection (HCI) Effect has a significant impact on their reliability, manifesting as threshold voltage shift and increased leakage current, thereby limiting their widespread commercial deployment. We conducted simulation analysis to investigate the effects of different trap energy levels and densities on device performance, revealing the important influence of the HCI effect on the transport characteristics of GaN MIS-HEMTs. The findings provide a theoretical basis for improving the reliability of GaN MIS-HEMTs and advancing their commercialization.

Keywords

MIS-HEMTS; Reliability; HCI; Simulation; Transport Characteristics.

1. Introduction

Power devices play a vital role in power systems as they are responsible for regulating and converting electrical energy in various applications such as renewable energy systems, electric vehicles and industrial motor drives. As the demand for higher power conversion efficiency and higher switching speed continues to grow, developing a new generation of semiconductor devices to replace traditional silicon-based semiconductors is key to meeting the changing needs of power electronics[1]. GaN High Electron Mobility Transistors (GaN HEMTs) distinguish themselves due to the unique properties of GaN material and the polarization characteristics of the AlGaN/GaN heterostructure. These devices exhibit high power density, excellent thermal performance, and fast switching speed. Such characteristics make HEMTs the preferred choice for high-frequency and high-power applications, particularly in fields such as communications, radar, power systems, and electric vehicles[2].

The recessed-gate GaN MIS-HEMT (MIS-HEMT) has emerged as a promising variation of the traditional GaN HEMT. MIS-HEMT devices integrate an insulating layer between the gate and the semiconductor material, it provides a larger gate swing, higher V_{TH}, and lower gate leakage[3]. These advantages make MIS-HEMTs an ideal candidate for next-generation power devices, especially in applications requiring high voltage and efficiency. The recessed gate is typically fabricated using dry etching techniques, with chlorine-based dry etching processes commonly employed. However, the reliability issues have hindered the further development of Recessed Gate AlGaN/GaN MIS-HEMT devices[4]. Meanwhile, the existing processes for gate formation introduce numerous defects in the devices. Therefore, it is crucial to investigate how these device defects impact electrical performance and gate reliability.

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The hot carrier injection (HCI) effect is a long-term degradation mechanism that can lead to severe reliability issues in devices, such as threshold voltage, transconductance, saturation drain current, and gate leakage current[5]. The degradation of these electrical characteristics can significantly affect the switching speed and functionality of circuits, potentially causing catastrophic device failure. Long-term reliability testing and analysis of products are primarily conducted through accelerated life testing (e.g., increasing voltage, applying high temperatures), which requires substantial time and financial investment. In this paper, Technology Computer-Aided Design (TCAD) simulation modeling software is utilized to simulate the impact of the HCI effect on device performance. Initially, we conduct reverse engineering on a exact device to extract its parameters and construct a comprehensive physical model by TCAD simulation . This facilitates the simulation and analysis of the influence of the hot carrier injection (HCI) effect on the degradation characteristics of the device's gate, as well as its threshold voltage and other associated electrical properties.

2. Device Model Building

To ensure the validity and accuracy of the simulation results, the physical model developed in this study is parameterized using actual data from commercially available E-mode GaN HEMTs. Chemical decapsulation was performed using a mixture of nitric acid (HNO_3) and sulfuric acid (H_2SO_4), in a 3:1 ratio to remove the package. We employed Focused Ion Beam (FIB) to perform cross-sectioning of the device under test, and used Scanning Electron Microscope (SEM) to observe the cross-sectional view of the recessed-gate GaN MIS-HEMT device. These key parameters were extracted from these observations. Figure 1 illustrates the cross-sectional view and magnified images of the device under the FIB-SEM observation system, while Table 1 presents the vital parameters of the device under test.

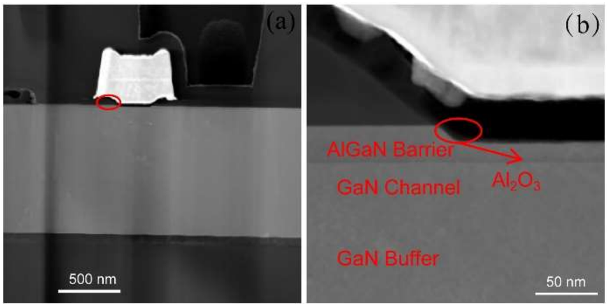

Figure 1. (a) The SEM image of the cross-sectional structure of the DUT.
(b) The locally enlarged SEM image of Figure 1.(a).

Table 1. Physical parameters of the DUT according to experiment.

Parameters	Values	Explanation
L_{gs}	1.2μm	Gate-source distance
L_{gd}	4.3μm	Gate-drain distance
L_s	0.5μm	Source length
L_d	0.5μm	Drain length
$T_{barrier}$	30nm	AlGaN Barrier thickness
T_{buffer}	1.6μm	GaN Buffer thickness
$T_{channel}$	11nm	Depth of recessed-Gate

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The recessed-gate GaN MIS-HEMT typically utilizes fluorine ion etching to form the gate recess structure in the AlGaN barrier layer. The gate contact is of a Schottky type, and the device operates in a normally-off mode by depleting the two-dimensional electron gas (2DEG) beneath the gate during turn-off. However, etching the AlGaN barrier layer introduces defects, which can adversely affect the mobility. To enhance the performance of the transistor, materials with a high dielectric constant are typically selected for the gate dielectric. The gate dielectric material is determined to be Al_2O_3 based on results obtained from cross-sectional observations[6]. Compared to the traditional SiO_2 material, aluminum oxide (Al_2O_3) possesses a higher dielectric constant (~20–30) and a narrower band gap, offering superior charge storage capability, making it suitable for use as a high-k gate dielectric material in advanced semiconductor devices[7]. The two-dimensional structure of the recessed gate GaN MIS-HEMT device is shown in Figure 2.

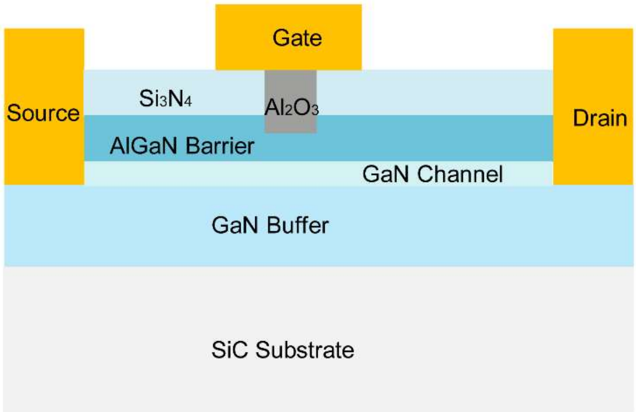

Figure 2. Schematic diagram of the cross-section of the recessed gate GaN MIS HEMT device.

2D simulations are typically conducted using TCAD simulation software. Based on experimental data, a structural model of the recessed gate GaN MIS-HEMT device was developed, with a global definition of n-type background doping for the device. Specifically, due to the consideration of simulation software's characteristic requirements, the source/drain contact metal is defined as Ni/Al. N-type heavy doping is applied to the source and drain ohmic contacts, with a doping concentration of 5×10^{20} cm^{-3} eV^{-1}, in order to simulate the non-local tunneling effects at the source and drain. The polarization effect due to strain in the AlGaN barrier layer and its contact region with the GaN channel layer is defined with the polarization direction oriented toward the SiC substrate. In the device, both Shockley-Read-Hall (SRH) and radiative recombination models are defined, as the doping levels determine the electron concentration in the channel, the scattering mechanisms of the charge carriers, and the electrical characteristics of the device. Furthermore, when electrons in the GaN HEMT are subjected to a high electric field, their velocity reaches saturation. Therefore, a corresponding mobility model is defined in the simulation physical model of the recessed gate GaN MIS-HEMT to account for this effect.

The Hot Carrier Injection (HCI) effect refers to the phenomenon in which charge carriers in the GaN HEMT are accelerated to sufficiently high energies under high electric field conditions, while becoming hot carriers. These hot carriers can be injected into the gate oxide-semiconductor interface or directly into the oxide layer itself, thereby affecting the device's performance. To make the simulation results more evident, a control experiment is set up in the device simulation to investigate the HCI effect. Specifically, a comparison is made between simulations where no trap physical model is defined at the gate oxide-semiconductor interface and those where the trap physical model is included, providing a clear contrast for the simulation analysis.

Figure 3(a) shows the polarization charge distribution of the device. From the figure, it can be observed that a high concentration of two-dimensional electron gas (2DEG) is induced at the

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AlGaN/GaN interface. Since the majority carriers in the GaN HEMT device are electrons and the minority carriers are holes, Figure 3(b) shows the electron mobility distribution of the recessed gate GaN MIS-HEMT. The electron mobility of the 2DEG formed between the AlGaN barrier and the GaN buffer layer is 1592 $cm^2 \cdot V^{-1} \cdot s^{-1}$, which is consistent with the 2DEG concentration reported in the literature.

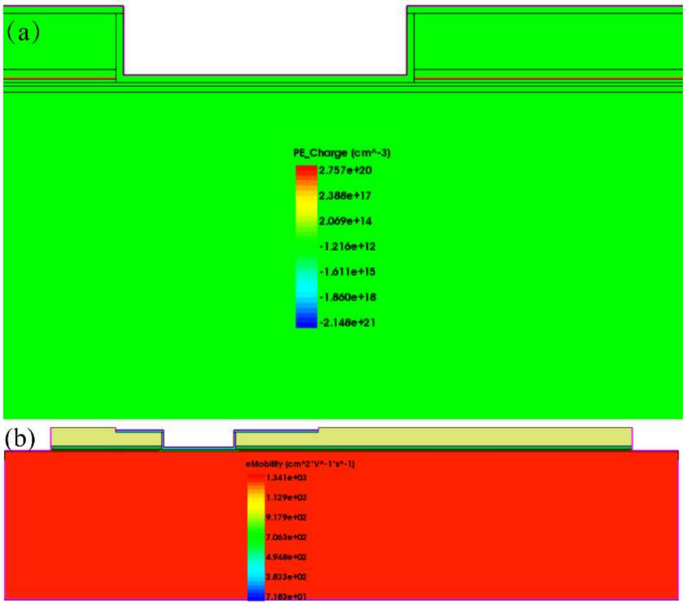

Figure 3. (a) The polarization charge simulation distribution diagram of the MIS-HEMT in the off-state.(b) The electron mobility simulation diagram of the MIS-HEMT under zero voltage bias.

3. HCI Effect Simulation

To investigate the degradation of the electrical parameters of the recessed gate GaN MIS-HEMT under the influence of the HCI effect, we set receptor trap densities of 1×10^{13} (cm^{-2} eV^{-1}), 1×10^{14} (cm^{-2} eV^{-1}), and 1×10^{15} (cm^{-2} eV^{-1}), respectively[8]. Additionally, shallow and deep trap energy levels were defined, located at 0.2 eV and 0.6 eV from the conduction band edge (E_c), respectively. The defect model used for simulating the device is summarized in Table 2. When the receptor trap concentration of the device is 1×10^{13} (cm^{-2} eV^{-1}) and the trap energy level is deep, with a value of 0.2 eV from the conduction band edge (Ec), the simulation results of the trap concentration and the trap concentration at the interface boundary are shown in Figure 4.

Table 2. Trap effect simulation parameters of GaN HEMT devices.

Trap simulation parameters setting						
Trap level	Ec 0.2eV	Ec 0.2eV	Ec 0.2eV	Ec 0.6eV	Ec 0.6eV	Ec 0.6eV
Trap type	acceptor	acceptor	acceptor	acceptor	acceptor	acceptor
Density ($cm^{-2}eV^{-1}$)	1×10^{13}	1×10^{14}	1×10^{15}	1×10^{13}	1×10^{14}	1×10^{15}
Location	AlGaN /Oxide	AlGaN /Oxide	AlGaN /Oxide	AlGaN /Oxide	AlGaN /Oxide	AlGaN /Oxide

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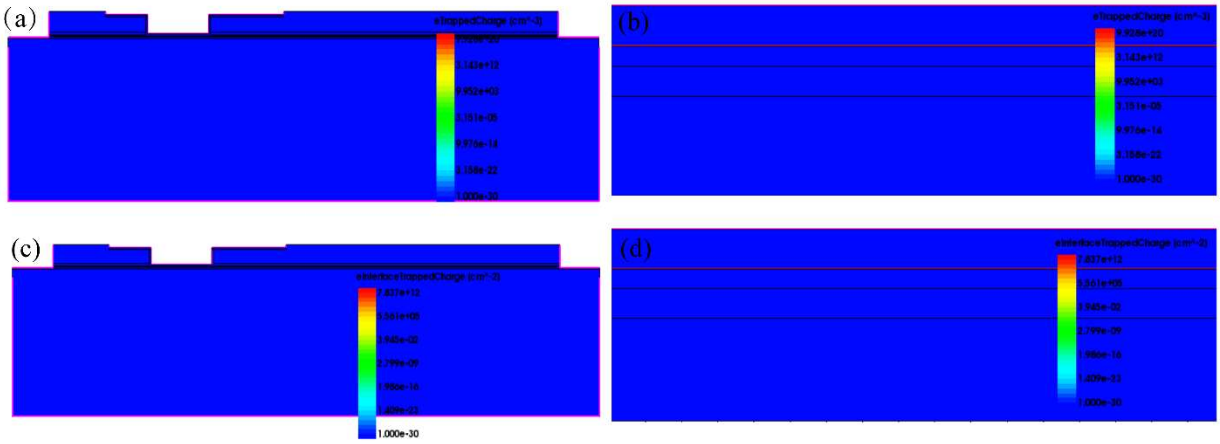

Figure 4. (a) Simulation distribution diagram of receptor traps charge capture in the device.
(b) Zoomed-in simulation diagram of receptor traps charge capture in the device.
(c) Simulation distribution diagram of receptor traps charge capture at the AlGaN/Oxide interface in the device.
(d) Zoomed-in simulation diagram of receptor traps charge capture at the AlGaN/Oxide interface in the device.

Specifically, we conducted electrical characteristic simulation and testing for the MIS-HEMT device, with the device's transfer characteristic curves shown in Figures 5(a) and 5(b). As the gate voltage increases, the threshold voltage of the device shifts. This phenomenon may be due to the injection of hot carriers or hot ions into the gate oxide region, leading to a change in the effective control of the channel by the gate. Carrier trapping and release at the AlGaN/Oxide interface results in variations in the threshold voltage. As the gate voltage increases, the drain current decreases. This could be attributed to the trapping of free carriers by the interface states, effectively reducing the carriers that contribute to the drain current. This phenomenon may be associated with Trap-Induced Barrier Lowering (TIBL), where traps at the interface modulate the potential barrier, lowering the conductive barrier and thereby reducing the drain current at higher gate voltages. Comparing Figures 5(a) and 5(b), it is evident that high-level acceptor traps have a more significant impact on the performance of the MIS-HEMT device, with a more pronounced reduction in both the threshold voltage and drain current.

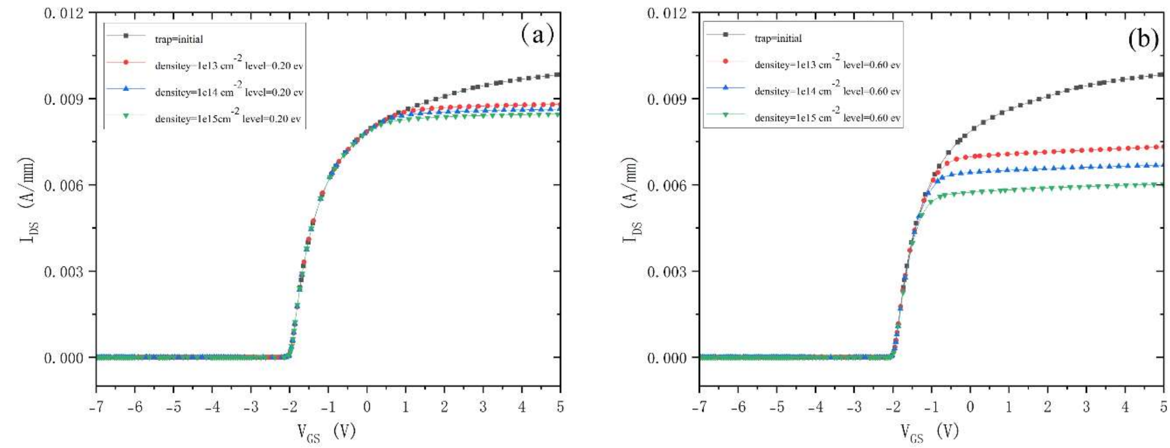

Figure 5. (a) Device transport characteristics curves when the trap energy level is Ec +0.2 eV.
(b) Device transport characteristics curves when the trap energy level is Ec +0.2 eV.

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4. Conclusion

In this study, we characterized commercially available MIS-HEMT devices through reverse engineering to obtain their corresponding key parameters. A two-dimensional physical model of the recessed gate GaN MIS-HEMT was established via simulation, and the HCI effect of the MIS-HEMT was investigated using TCAD simulation software. The threshold voltage shift and the reduction in drain current are primarily influenced by the trap density and trap energy levels. Deeper trap energy levels and higher trap densities have a more significant impact on the device performance, as they more effectively capture carriers, altering the device's electrical environment. The cumulative effect of traps can modify the charge transport characteristics of the device, which may lead to both beneficial effects (such as reduced leakage current) and detrimental effects (such as threshold voltage shift). The results of this study provide valuable insights for engineers in further improving and optimizing MIS-HEMT devices.

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