

國立中山大學
物理學系

博士論文

氮化鎵高電子遷移率電晶體可靠度
與物理機制研究

研究生：林好珊

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Doctoral Dissertation

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Research on Reliability and Physical Mechanism of

GaN High Electron Mobility Transistor

研究生：林好珊

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摘要

氮化鎵高電子遷移率電晶體 (GaN HEMT) 因其材料特性優異，擁有寬能隙、高電子遷移率以及熱穩定性佳，以上優勢得以實現良好的線性度、高崩潰電壓、高功率及電流密度。此外，GaN HEMT 也利於高頻率操作應用，使其成為射頻 (RF) 5G 通訊發展的主流候選者。即使隨著快速發展，許多 GaN HEMT 性能與可靠度問題仍然存在並需要解決，特別是與塊材材料中的原生缺陷息息相關。本文針對蕭特基及金屬/絕緣體/半導體 高電子遷移率電晶體 (Schottky- & MIS-HEMT) 操作時發現的特殊行為進行性能及可靠度分析以及提出物理機制。同時研發出低溫超臨界鈍化技術(SCF)消除 GaN HEMT 缺陷，提升開態電流(I_{on})、降低接觸電阻(R_s)，提升元件性能。

首先深入分析 GaN HEMT 在開關操作過程中觀察到的扭結效應機制。當扭結效應發生，汲極電流-閘極電壓(I_D-V_G)顯示電流下降和閾值電壓 (V_T) 正偏移有關。通過 Silvaco 模擬缺陷位置及照光實驗，扭結效應後的 I_D-V_G 對紅光、綠光或藍光照射沒有反應，但對紫外光有反應。這意味著去除缺陷中的電子不能恢復扭結效應引起的 V_T 飄移，證明碰撞游離產生的電洞是扭結效應的關鍵。綜合以上，提出碰撞游離產生的電洞與緩衝層中被捕獲電子的複合是扭結現象的主要機制。接著，接續研究 GaN HEMT 扭結效應中特別的電流弧形節點。汲極電流和汲極電壓(I_D-V_D) 正向和反向輸出曲線顯示，當 V_G 增加時節點呈弧形趨勢。利用長時間電壓應力和恢復量測技術於弧節點，證實弧節點的位置與碰撞游離的程度有關，同時代表產

生的電洞數量。此外，透過 C-V 測量更證實電洞是由碰撞游離產生並位於閘極邊緣處，這也將通過變溫實驗進行驗證，完整提出扭結效應節點的物理模型和劣化行為。由於 GaN HEMT 在製程中易產生晶格不匹配，產生差排(dislocation)或氮空位(N-vacancy)缺陷，影響元件特性。除了釐清可靠度議題之外，缺陷鈍化也至關重要。利用超臨界流體的物理及化學性質與固、液、氣三相的特性不同，開發出低溫超臨界鈍化技術，鈍化 GaN HEMT 缺陷有效提升 I_{on} ，降低 R_s ，提升元件性能。

最後則是系統地討論了 MIS- GaN HEMT，在關態操作下 V_T 的異常兩階段劣化現象。在關態操作期間，閾值電壓在短時間內正向飄移接著負向飄移。相反，關態的閘極漏電在長時間應力中持續減少。不同測量條件的結果顯示，足夠的橫向電場下將產生電子電洞對，其分別被捕獲在不同閘極介電層位置，兩者互相抗衡 V_T 的漂移方向。此外，透過變溫實驗得知關態期間是來自閘極的載子引起的碰撞游離並且隨著溫度而上升。最後，透過不同閘極絕緣體 (GI) 厚度的元件驗證並提出劣化行為的物理模型。

關鍵字：高電子遷移率電晶體，氮化鎵，扭結效應，關態應力，超臨界流體，缺陷鈍化

Abstract

High breakdown voltage, high power, and current density are all achievable with high electron mobility transistors based on GaN (GaN HEMTs). GaN HEMTs also provide enhanced interference protection and significant promise in RF microwave and power electronics applications. However, there are still a lot of performance and reliability challenges that need to be resolved, particularly those involving flaws in semiconductor materials. In this research, the operational performance and the dependability of Schottky and metal-insulator-semiconductor high electron mobility transistors (Schottky - & MIS-HEMTs) are explored, and the relevant physical processes are proposed. Additionally, a low-temperature supercritical fluids (SCF) post-processing technique has been created to enhance component performance and reliability, passivate GaN HEMT flaws and efficiently boost the on-current (I_{on}) of GaN HEMT.

In the research, the mechanism of the kink effect during the drain current-drain voltage (I_D - V_D) of Schottky HEMTs on SiC is carefully analyzed. When the kink effect occurs, the drain current-gate voltage (I_D - V_G) curve shows that the drop in current is linked to an increase in the threshold voltage (V_T). Through Silvaco's simulated defect localization and lighting studies, it is discovered that I_D - V_G reacts to UV light but not to blue, green, or red light following the kink effect. As a result, the V_T shift-induced kink effect is eliminated since electrons cannot be released from the defect. The reliance of the

kink effect mechanism's reliance on the recombination of electrons and holes in the buffer layer has been demonstrated. The major mechanism allegedly responsible for the kink effect is caused by impact ionization (I.I.) and trapped electrons in the buffer layer and the hole recombination.

Continues to study the special current arc nodes in the kink effect of GaN HEMTs. The forward and reverse output curves of I_D - V_D show that the node tends to arc as the V_G increases. Using With long-term voltage stress and the recovery measurement technology at the arc node, it is confirmed that the position of the arc node is related to the degree of I.I. and also represents the number of holes generated. In addition, the C-V measurement confirms that the hole is generated by the I.I. at the gate edge, which will also be verified by the temperature change experiment, and the physical model and the degradation behavior of the kink effect node will be completely proposed.

Lattice mismatch is a common occurrence in the GaN HEMT process, which causes nitrogen vacancy or dislocation defects to emerge during the epitaxial process, lowering the performance and the reliability of the device. In the first two chapters, the issues regarding dependability are also clarified; the defect passivation is critical for GaN HEMTs. Furthermore, will take advantage of the physical and chemical qualities of SCF and the traits of solid, liquid, and gas phases to develop low-temperature SCF post-

processing technology, so as to deal with passivation GaN HEMT defects, effectively improve GaN HEMT I_{on} , reduce R_s , and improve component performance and reliability.

Finally, the atypical two-stage degradation of V_T under MIS GaN-HEMT off-state operation is thoroughly covered. The V_T shifts briefly positively and then negatively during the off-state operation. In contrast, the gate leakage (I_G) keeps getting smaller as in the off-state stress process. The experiment outcomes show that electron-hole pairs are created when a transverse electric field is strong enough. The created electrons and holes are then trapped on the Si_3N_4 gate insulator (GI), where they work to offset the V_T tendency to shift in one direction. Additionally, it has been established through the temperature change experiment that the I.I. is a dangerous condition that is brought on by carriers from the gate during the off-state. Finally, a model is verified and suggested with various GI thicknesses.

Keywords: HEMT, GaN, Kink effect, off state stress, supercritical fluids (SCF), Defect passivation

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