國立中山大學物理學系

博士論文

Department of Physics

National Sun Yat-sen University

Doctoral Dissertation

鰭式場效電晶體與
氮化鎵高電子遷移率電晶體可靠度機制研究

Research on Reliability Mechanism of Fin-Field Effect Transistor and GaN High Electron Mobility Transistor

研究生：邱豐閔

Fong-Min Ciou

指導教授：張鼎張 博士

Dr. Ting-Chang Chang

中華民國 112 年 1 月

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論文審定書

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本校物理學系博士班

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於中華民國 111 年 12 月 4 日經本委員會審查並舉行口試，符合博士學位論文標準。

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指導教授(張鼎張) 張鼎張 (簽名)

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6 年多的博士生涯即將結束，這一路走來跌跌撞撞，除了說不盡的辛酸，也有許多難忘的回憶。首先，我要感謝我的指導教授張鼎張老師，提供了完善的設備和豐富的資源，給予我十分優良的學習及研究環境，讓我順利翻轉人生做到我從未想過的事情，在這段期間您的言教及身教對我來說是最大的寶藏，您極富效率的思考邏輯成為我解決問題時的準則，您教授知識是我未來競爭所需的資本，最重要的是學習您對待對任何事物全心全意地專注以及堅持的態度，相信真正讓我翻轉人生的是從您身上學習到的種種。接著非常感謝我的口試委員張澤恩處長、莫亦先主管、陳伯勳老師、蔡宗鳴老師，對於我的博士論文提供了許多寶貴的建議與見解，讓我的博士論文能夠更加完善。

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邱豐閔 謹識

2023.1 冬中山

摘要

於 1960 年貝爾實驗室成功製作第一顆電晶體起，隨著摩爾定律(Moore’s Law)的發展，半導體科技蓬勃的成長逐漸變成科技發展的指標，時至今日，半導體製程技術持續在各個方面上引領科技的進步。首先基於原先 Moore's Law 的腳步上，現今半導體製程技術受益於極深紫外光設備(EUV)的出現，使得微縮節點達到了 3nm 的製程節點，但相對的製程成本以及製程良率同樣受到很大的挑戰。因此在接續微縮節點的開發中，矽基場效電晶體同時面臨元件微縮的物理極限以及高額的開發成本，使得摩爾定律的實現越來越難以達成。第二個發展面向則是，藉由整合多種系統功能晶片的方式，同時實現 IC 的功能提升以及微縮的超越摩爾(More than moore)。相比摩爾定律，More Than Moore 並不受限於單一電晶體尺寸微縮，更能達到低成本多功能的目標。最後則是因應在電動車與 5G 通訊蓬勃發展的時代，Si 材料特性限制電源轉換的效率以及操作的頻率，寬能矽(Wide-band-gap)的氮化鎵及碳化矽被視為第三代半導體材料並受到市場的重視，其中尤以氮化鎵，基於寬能隙、高電子飽和速度、高臨界電場等材料特性，不論是在充電應用的電子產品、5G 通訊的基站或是車用電子元件， GaN high electron mobility transistor (GaN HEMT)都具有極大的潛力。

本論文於第三章節中分析元件尺寸微縮下 n-FinFET 與 p-FinFET 的熱載子劣化機制。隨著增加熱載子劣化條件的閘極電壓，p-FinFET 的臨界電壓的漂移量比

n-FinFET 更早出現異常的增加。並透過萃取兩者$\tau \times (\frac{I_B}{I_D})^{-2.7}$ - I_D的分佈發現多重振動激發(Multiple-vibration excitation, MVE)在 p-FinFET 中比 n-FinFET 更容易發生，並導致嚴重的臨界電壓飄移。

接著於第 4 章節中討論 p-FinFET 在高溫負偏壓應力(Negative bias temperature instability, NBTI)下對關態下漏電的影響。發現在 NBTI 後 p-FinFET 於線性區的關態漏電有異常上升的情形，並在不同溫度量測下發現漏電與溫度呈正相關。透過線性區電流的正掃以及反掃特性與熱載子劣化的表現比較，發現關態下線性區的異常漏電是來自於缺陷輔助熱場發射所引發的產生電流。

在眾多系統功能晶片中，驅動 IC 以及電源管理 IC 是不可或缺的存在，而 3D 結構的 FinFET 雖然容易微縮，但難以符合耐壓的需求。因此第五章節中分析透過調整 nLDD 區域的摻雜以實現 Fin 結構下的 HV FinFET 的特性以及可靠度。我們發現 nLDD 處的硼摻雜能透過增加 nLDD 處的空寬度而抑制熱載子劣化，但同時發現硼摻雜時的擴散同樣會影響元件的可靠度，因此我們比較了不同氟摻雜濃度對熱載子劣化的影響，隨著氟摻雜濃度的增加，不論臨界電壓、跨導或是次臨界擺幅在熱載子劣化下都表現出更好的可靠性，並且發現氟濃度增加元件劣化區域越集中在汲極區域。最後透過隨機電報訊號的分析，證實硼擴散確實會降低元件可靠度，並提升高頻訊號的雜訊。

於第六章中，則是針對第三代半導體 GaN HEMT 在半導通狀態下熱電子應力(Hot Electron Stress, HES) 的臨界電壓(V_T) 劣化機制。此章節主要分析 GaN HEMT

於熱電子劣化後，於恢復期間觀察到 V_T 持續向正方向移動的異常現象。我們提出一模型解釋此現象，由於在 HES 期間處於高汲極電壓狀態，通道中的電子受橫向電場加速，在通道中產生熱電洞，電洞與預先存在的緩衝缺陷中的俘獲電子複合，使得在恢復過程中，通道中的電子重新填充緩衝層中未被佔據的缺陷，導致 V_T 發生嚴重的正向偏移。接著透過單一閘極偏壓條件的負偏壓應力 (NBS) 測試以及光照恢復和 Silvaco 模擬結果證實了 HES 回復期間異常的 V_T 飄移是由於通道電子回填緩衝層中的缺陷導致。

關鍵字: 鰭式場效電晶體, 熱載子效應, 負偏壓溫度不穩定性, 隨機電報訊號 ，氮化鎵高電子遷移率電晶體

Abstract

Since Bell Labs successfully manufactured the first transistor in 1960, the rapid advancement of semiconductor technology has progressively grown to be a significant indication of technological advancement thanks to Moore's Law. Now, semiconductor manufacturing technology continues to lead the advancement of technology in all the aspects. First, based on the footsteps of the original Moore's Law, nowadays semiconductor manufacturing technology has benefited from the emergence of extremely deep ultraviolet (EUV)-making the scaling node reach the 3nm, but the relative process cost and the process yield are also greatly affected. As a result, it becomes increasingly challenging to realize Moore's Law as new scaling nodes are developed and silicon-based FETs are constrained by physical scaling laws which generates significant development cost. The second development direction focuses on the improvement of the performance and the miniaturization of integrated circuits by integrating multiple system function chips, which is called More Than Moore. Compared with Moore's Law, More Than Moore is not limited to the size reduction of a single transistor, but capable of achieving the goal of low cost and multi-function instead. Finally, in response to the booming era of electric vehicles and 5G communications, the characteristics of Si materials limit the efficiency of power conversion and the frequency of operation. Wide-band-gap Gallium nitride and silicon carbide are examples of the third-generation semiconductor materials

that are valued more and more by the market. In particular, gallium nitride is based on wide band gaps, high critical electric fields, and high electron saturation velocities, which makes it the basis for GaN high electron mobility transistors (GaN HEMTs), which are highly effective in consumer electronics products such as fast charging applications, base stations for 5G communication, or automotive electronic components.

As a result, in Chapter 3, how the scaling of the device size affects the hot carrier degradation process of n-FinFET and p-FinFET is examined. It is discovered that the threshold voltage shift of p-FinFET grows abnormally earlier than that of n-FinFET with the gate voltage of the hot carrier degradation condition raised. Besides, by extracting the distribution of both $\tau \times (\frac{I_B}{I_D})^{-2.7}$ - I_D, it is found that multiple-vibration excitation occurs more easily in p-FinFET than in n-FinFET, which leads to a severe threshold voltage shift.

In Chapter 4, the off-state leakage generated by p-FinFET under the instability test at high temperatures with negative bias temperature instability is discussed. In the linear region, it is discovered that the off-state leakage of p-FinFET rises abnormally after NBTI and that the leakage is positively connected with temperature based on the various temperature measurements. It is discovered that the anomalous leakage current in the linear area is produced by trap-assisted thermal field emission by the comparison of the forward and reverse sweep characteristics of the current in the linear region and the performance of the hot carrier degradation. Therefore, in Chapter 5, the characteristics and reliability of HV FinFETs under the Fin structure is analyzed by adjusting the doping of the nLDD region.

Among many system function chips, driver ICs and power management ICs are indispensable. Although FinFETs with 3D structures are easy to shrink, it is difficult to meet the requirements of high voltage operation. It is found that boron doping at the nLDD can suppress the hot carrier degradation by increasing the void width at the nLDD and that the diffusion of boron doping also affects the reliability of the device. Therefore, the comparison of the effects of different fluorine doping concentrations on the hot carrier degradation is made. Transconductance or subcritical swing exhibit better reliability during the hot carrier degradation with fluorine doping concentration increasing, regardless of the threshold voltage, and it is discovered that with fluorine concentration increasing, the degradation region of the device is concentrated more in the drain region. Finally, through the analysis of random telegraph signals, it is confirmed that the boron diffusion will indeed reduce the reliability and increase the noise of high-frequency signals.

The hot electron stress (HES) degradation process in the semi-on state of the GaN HEMT is covered in Chapter 6. This chapter examines the unusual occurrence when V_T keeps shifting in the positive direction, following a hot electron stress; such trend is

continued during the recovery phase. Here is a model that is put out to account for this occurrence. As a result of the high drain voltage state experienced during HES, hot holes are created in the channel due to the channel's electrons being accelerated by the lateral electric field. These holes then recombine with trapped electrons in the buffer defects which causes a significant positive shift in V_T. Finally, it is established through the measurements of negative bias stress (NBS), light recovery, and the results of Silvaco simulations that the aberrant V_T shift during recovery is caused by channel electrons refilling the buffer defects.

Keywords: FinFETs, Hot Carrier stress, Negative bias temperature instability, Low noise frequency, GaN HEMT

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