多重能量氧離子佈植絕緣氮化鎵/氮化鋁鎵高電子遷移率異質接面場效電晶體

研究生：邵宜暄　　指導教授：張翼博士

國立交通大學材料科學與工程研究所

摘要

由於在高功率以及高溫環境下操作的潛力，以氮化鎵系列材料製作的電子元件近年來越來越受到矚目。氮化鋁鎵/氮化鎵異質接面高電子遷移率場效電晶體由於具有材料上優良的物理性質，諸如寬能隙以及隨之而來的高崩潰電場($5*10^6$V/cm)，高電流密度以及良好的熱穩定性。使得氮化鋁鎵/氮化鎵異質接面高電子遷移率場效電晶體適合高功率以及高溫環境下的應用。對於此種電子元件的絕緣製程，現在一般在使用的方法是利用乾式蝕刻來吃掉要絕緣的部分，定義出元件的 active 區域。但是用乾式蝕刻吃出的 active 區域平台的邊緣部份是垂直的，像懸崖一樣沒有一個坡度，很容易造成連接閘極的金屬導線在平台邊緣斷線，使得我們蝕刻深度不能太深。更大的問題是，在現在主流 Ga-face 極性磊晶成長氮化鋁鎵/氮化鎵異質接面高電子遷移率場效電晶體結構中，電子會由二維電子氣經由閘極金屬導線與二維電子氣接觸的部分，傳導出來聚積在表面閘極與汲極之間靠近閘極的地方。這些聚積的電子可能會對二維電子氣由於電性相斥

的原因排斥二維電子氣中的電子(depletion)，就好像多出一個小的閘極一樣造成電流密度的降低。也可能造成I-V曲線中，隨著汲極電壓的上升,更多的電子聚積在表面造成汲極電流下降稱為current-slump效應。如果我們使用平面化的離子佈值絕緣製程來取代乾式蝕刻，就不會有以上斷線以及電子從導線與二維電子氣接觸的地方跑出來聚積的問題，絕緣的效果也比乾式蝕刻來的好，飽和電流跟崩潰電壓比起乾式蝕刻絕緣的元件都有所增加。我們在實驗的過程，是先用不同間距的片狀鈦/鋁/鎳/金歐姆接觸區域，用不同能量與劑量的氧離子施以多重能量氧離子佈值, 讓他們彼此之間絕緣, 來測試絕緣效果。後來在元件製程上是用180+90+75+30KeV四種不同能量氧離子依序佈值, 每個能量用$5*10^{14}/cm^{2}$劑量來多重能量氧離子佈值絕緣。我們發現剛佈值完並不是絕緣效果最好的條件，佈值後經過200~300度C一個小時的爐管退火後，由TEM的影像中我們可以發現缺陷比起剛佈值完會稍微聚集凝結，使得缺陷間距離增加減少電子在缺陷間的跳躍傳導，達到最好的絕緣效果。我們也發現300度C 1小時退火後會產生垂直C軸的片狀缺陷,並且在靠近表面的部分一層一層的由結晶態GaN轉變成非晶質GaN而有著一個非常平整的晶質與非晶質介面。隨著退火溫度的增加，在850度1小時退火後的TEM照片中我們看到了非晶質的GaN重新成核成長成為多晶的GaN，

使得電流經由晶界導通造成漏電增加降低絕緣效果。除了 TEM 之外，我們也用 AFM 量測離子佈值前後以及佈值完高溫長時間退火後的表面，發現表面的平坦度幾乎都沒有變化，證實了我們這個條件的多重能量氧離子佈值絕緣相當適合應用在元件的平坦化製程上。

在經過絕緣效果的測試以及材料分析後，我們把多重能量氧離子佈質絕緣的製程實際使用在元件的製作上。我們使用光阻來當作離子佈值時的光罩防止 active 區域受到離子的轟擊，使用多重能量氧離子佈值絕緣製程的高電子遷移率異質接面場效電晶體，與傳統乾式蝕刻絕緣的比起來，有較高的飽和電流值 668mA/mm，較高的 off-state 閘極與汲極間崩潰電壓 87 伏特，較大的 transconductance 288mS/mm 以及比較不明顯的隨電壓增加電流下降的情況。由此可知，多重能量氧離子佈值絕緣製程的氮化鋁鎵/氮化鎵異質接面高電子遷移率場效電晶體比起用乾式蝕刻絕緣製程的，除了平坦化以及步驟較少外元件的效能上也有所改善，值得我們把多重能量氧離子佈值絕緣製程應用在元件的製程上。

Multi-Energy Oxygen Ion Implantation Isolation for AlGaN/GaN HEMTs

Student: Shoau Yi Shan Advisor: Dr. Edward Y. Chang

Department of Materials Science and Engineering
National Chiao Tung University

Abstract

GaN-based electron devices have received much attention due to their ability to operate at high power level and high temperature environment .Physical characteristics of AlGaN/GaN HEMTs like large energy bandgap, high electric breakdown field($5*10^6$V/cm), high current density and good thermal stability make AlGaN/GaN HEMTs suitable for high power and high temperature applications. The contemporary isolation method is by using dry etch to define the device active region. But it's difficult to dry etch GaN with a sloped side instead of a vertical cliff, which limits the etched depth since the connection metal lines may disconnect at deep vertical etched mesa sides. Moreover, in Ga-face polarization AlGaN/GaN structure, electrons which come from 2DEG may flow through the contact of gate metal line and accumulate at the surface region near the gate. This phenomenon may result in high gate leakage current and reduces G-D breakdown voltage. If the HEMT structure is the Ga-face polarization structure, electrons which accumulate at the surface may produce the current slump behavior that is often seen in the Id-Vd curve. Ion implantation, however, is a planar

process which can avoid the problems mentioned above. Moreover, we discovered in our experiment that with proper implantation energy and ion dosage, ion implantation is a better isolation process than mesa dry etch. The saturation current I_{dss} is also improved. In our experiment, oxygen ions with different energies were multi-implanted into the AlGaN/GaN HEMT structure wafers. The energies used were 180kev + 90kev +75kev +35kev in sequence with the same $5*10^{14}cm^{-2}$ dosages for each energy. First, Ti/Al/Ni/Au ohmic contact pads with different distances were used for implantation masks and then the leakage currents between the pads were measured to estimate isolation quality. Post heat treatments including RTA and tube annealing were then applied to test the thermal stabilities. The leakage current between ohmic contact pads reached minimum value after 300℃ 1hr post-annealing. It is because hopping conduction was suppressed after defect clustering. And the leakage current arose at higher post-annealing temperatures with the formation of polycrystalline GaN at the implantation damaged region. XTEM pictures for un-implanted, as-implanted, 300℃ 1 hour post-annealed and 850℃ 1 hour post-annealed samples were taken . The pictures of 300℃ post-annealed sample showed defect clustering as compared with the as-implanted sample. Therefore, hopping conduction was reduced and isolation quality was improved. Layer-by-layer transition from crystalline GaN to amorphous GaN beginning at the surface was also observed in the 300℃ post-annealed sample. For pictures of 850℃ 1 hour post-annealed sample we found that polycrystallization from amorphous GaN occurred. As a result, leakage current would flow through grain boundary and degraded the isolation property. AFM measurements showed that surface roughness didn’t change after implantation and post-annealing process.

After the leakage current measurement and material analysis, we applied this process to the HEMT fabrication. The fabrication process used S1818 photoresist as the implantation mask and we had achieved a planar device with high saturation current of 668mA/mm, maximum current of 833mA/mm, off-state breakdown voltage of 87V for 4.5um G-D spacing and the peak transconductance was 288mS/mm. The current slump behavior was also suppressed as compared with the AlGaN/GaN HEMTs using ICP mesa dry etch for isolation. Overall, this study shows that the AlGaN/GaN HEMTs device was improved by using multi-energy oxygen ion implantation isolation process compared with the device formed by conventional dry etch mesa isolation.

致謝

我想，以我淺博的學識跟懶散的個性，能夠完成這樣一篇的論文，我真的要感謝很多一路上幫忙我的人。首先，我要感謝我的指導教授張翼博士，辛苦的維持住這整個龐大的實驗室，讓我有很多的資源可以使用，並且提供一些肯切的建議使我獲益匪淺。潘扶民博士張立博士與羅廣禮博士在材料分析上的不吝賜教也令我受用無窮。

接下來，我要感謝實驗室許許多多親切幫忙我的學長學弟妹們。徐金鈺與黃瑞乾學長從碩一開始就教導我這莽莽撞撞的學弟許多東西，不論是做事做實驗的態度，還有各種實驗上的知識。與謝炎璋學長及楊宗火喜學長在TEM方面也給了我相當多的指導與建議。吳雲驥學長也留下了許多寶貴的資料讓我少走寃枉路。沈柏村學長也很照顧我幫了許多忙。張晃崇學長與陳士鴻學長和葉協鑫彭怡瑄曾建堯跟呂宗育同學們在製程上也幫了許多忙。我可愛的學弟妹張家達跟林良郡也一路陪著奮鬥。光電所的王薏婷學妹也很夠義氣的幫我製作試片。沒有大家的幫忙與合作，我一個人一定做不到的。

最後，要感謝我的家人。爸爸媽媽讓我唸書沒有後顧之憂的完成兩年的學業，也讓我全心學到了很多的東西。還有我的女友，陪伴我走過讓我的心靈有個港灣。有你們，我才能一路一直走下去，我愛你們。

Content

Abstract (Chinese) Ⅰ

Abstract (English) Ⅳ

Acknowledge Ⅶ

Content Ⅷ

Chapter1. Introduction 1

Chapter2. Ion Implantation and Material Analysis Theory Background 5

2.1 Ion Implantation 5

2.2 Implantation Isolation 9

2.3 Material Analysis 10

2.3.1 TEM 10

2.3.2 ESCA 11

Chapter3. Test Process, Device Fabrication and Material Analysis Sample Preparation 16

3.1 Test Process 16

3.2 Device structure 17

3.3 Device Fabrication 17

3.4 Material Analysis Sample Preparation and Measurement 19

3.4.1 TEM Sample Preparation and Measurement 20

3.4.2 ESCA Sample Preparation and Measurement 20

Chapter4. Results and Discussion 23

4.1 Electrical Properties Results and Discussion 23

4.1.1 Isolation Results 23

4.1.2 DC Characteristics 23

4.2 Material Analysis Results and Discussion 26

4.2.1 TEM Results and Discussion 26

4.2.2 ESCA Results and Discussion 30

4.2.3 AFM Results and Discussion 31

Chapter5. Conclusion 51