國立中山大學
物理學系
博士論文
碳化矽功率元件與極化金氧半電容之物理機制
與可靠度研究
研究生：金福源
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Doctoral Dissertation

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指導教授：張鼎張 博士

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於中華民國 111 年 12 月 10 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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摘要

隨著近期的5G通訊、智慧聯網(AIOT)、電動車等科技的發展，高效能晶片(High Performance)與功率元件(Power Device)日趨重要，金氧半場效電晶體(MOSFET)是現今高效能晶片與功率元件中的主要元件，而MOSFET隨著應用領域差異而有不同的技術演進，功率元件中的MOSFET隨著電力與節能需求增加，如何降導通與切換損耗越來越受重視，矽基功率元件的製程技術結構構設計經過了多次結構和工藝優化更新，已逐漸接近矽材料的極限，而碳化矽(SiC)是最具潛力的寬能隙(Wide Band-gap)半導體，相對於矽(Si)，具有寬能隙(bandgap)、高的臨界電場(critical electric field)、導熱率(thermal conductivity)、電子飽和速度(electron saturation velocity)等特性，因此碳化矽(SiC)有望取代矽(Si)作為新一代的高功率元件材料，可應用於電動車、電源轉換器、智能電網、大型載具等，迄今，美、日、歐等國家已啟動多個大型研究計劃從事碳化矽(SiC)相關研究，顯現出碳化矽(SiC)在商業及軍用市場上的發展性與重要性。

應用於高效能晶片的MOSFET隨著Moore's law 持續微縮，此外，為了降低閾值電壓，閘極氧化層需要降低厚度，當微縮至1 nm厚度以下時，容易產生量子穿隧漏電，並導致閘極漏電上升。因此後續製程引入高介電常數氧化層，能在同樣的閾值電壓下，維持較厚的閘極氧化層厚度，降低漏電，此外，為了提升元件的操作頻率與操作速度，多晶矽閘極也被更換為金屬閘極，為了因應邏輯IC的閘極電壓需求，需要設計多種閾值電壓(V_T)的電晶體，目前主要以多層功函數金屬製程調變閾值電壓(V_T)，當電晶體從平面式結構進展至FinFET時，閘極功函數金屬能堆疊的空間越來越小，若持續以多層功函數金屬調變閾值電壓，將會提升閘極電阻，降低元件操作速度，因此，近期引入極化層製程，調變閾值電壓，透過在La、Al等元素摻入至氧化鉿，形成界面含氧密度差異層，並在在介面形成偶極，可降低與調整閾值電壓(Threshold voltage, V_T)。

本論文將針對碳化矽金氧半場效電晶體、碳化矽接面位障蕭基二極體之性能、極化金氧半電容的可靠度進行相關研究。

本論文第一部分研究SiC Junction Barrier Schottky 的逆偏電壓可靠度(Negative Bias Stress)，功率二極體主要做為開關及整流元件，最重要的參數為逆偏漏電、崩潰電壓、逆向恢復時間，分別影響元件性能與功率消耗，二極體經常使用Schottky，因為逆向恢復時間較短，適合高速切換，但逆偏漏電很大，產生額外功耗，Junction Barrier Schottky能兼顧schottky的低Trr與PN的低逆偏電流、高崩潰電壓，所以碳化矽功率二極體多使用此結構，SiC JBS目前是極熱門的元件，擁有低逆向恢復時間、高崩潰電壓(可達12000V)、低漏電、高熱穩定性，已有很多研究說明其相關特性與可靠度，然而卻較少說明可靠度機制，本文發現，在逆偏可靠度下，SiC JBS的V_{BD}有明顯上升，因此會針對逆偏可靠度下的V_{BD}變化深入探討。

本論文第二部分研究 SiC MOSFET 的逆偏電壓可靠度物理機制(Negative Bias Stress)，目前碳化矽 MOSFET 雖然已經大量商用化，但可靠度仍有未解議題，特別是閘極偏壓可靠度(Gate Bias Instablity)，其中又以負偏壓閘極不穩定度(Negative Bias Instbllity)最嚴重，因為碳團促(carbon cluster) 容易在閘極氧化層製程中引入並在介面或氧化形成缺陷，導致載子遷移率大幅下降與閾值電壓(Threshold voltage, V_T)不穩定，本研究 SiC MOSFET 的負偏壓閘極不穩定度(Positive Bias Stability /Negative Bias Instbllity)的機制，並進一步探討負偏壓閘極不穩定度的物理機制。

本論文第三部分研究極化金氧半電容器(Dippole MOSCAP) 的閘極正偏壓溫度不穩定性(Positive bias temperature instability, PBTI)，摻雜後的極化金氧半電容不僅有效降低 V_{FB}，同時也會提升元件的閘極氧化層電容值，並降低閘極漏電，但經過閘極正偏壓溫度不穩定性測試後，極化金氧半電容的劣化較嚴重，容易在氧化層產生電子注入與額外的氧化層缺陷，這是因為閘極正偏壓下，電子從通道通過穿隧經過二氧化矽到氧化鉿時，透過位能差產生動能，並對氧化鉿產生劣化，而介面偶極引起的能帶彎曲，使電子有較大的位能差，因此極化金氧半電容更容易產生電子

注入與缺陷產生。此外，時間相關介電層崩潰(Time dependent dielectric breakdown, TDDB)的數據也顯示極化金氧半電容有較短生命週期，代表極化金氧半電容雖能有效改善電性，但可靠度較差。

關鍵字:功率半導體元件、碳化矽、碳化矽接面位障蕭基二極體、碳化矽金氧半場效電晶體、極化金氧半場效電容

Abstract

With the recent development of technologies such as 5G communication, AIOT, and electric vehicles, the application of high-performance calculation (HPC) and power devices has been becoming increasingly important. Metal oxide half-field-effect transistors (MOSFETs) are main components in HPC and power components, and MOSFETs have different technical developments depending on the application field. With the increase in power demand and the rise of energy-saving awareness, how to reduce conduction and switching losses has become more and more crucial in power devices. For the application of Industry 4.0, the design and technology development of silicon(Si) components has undergone several structural changes and process optimization, which, however, has gradually approached the limit of silicon materials. Silicon carbide (SiC), one of the wide band-gap semiconductor materials, features wide bandgap, high critical electric field and high thermal conductivity, compared with Si. Therefore, SiC is expected to replace Si as a new high-power component material. The applications include power converters, automotive electronics, smart grids, large vehicles, etc. So far, the United States, Japan, Europe, and other countries have launched several large-scale projects to carry out related research, which shows the potential of silicon carbide (SiC) in the commercial and military markets.

MOSFETs used in HPC continue to shrink with Moore's Law, and the gate oxide layer is also scaling. When the oxide thickness is reduced to only 1 nm, quantum tunneling leakage is likely to occur, which results in additional gate leakage and reliability issues. Therefore, high dielectric constant is introduced, which can maintain excellent gate control force at a thicker physical thickness. To improve the operating speed of the device, the polysilicon gate is also replaced with metal gate. In order to meet the gate voltage requirements of logic IC, it is necessary to design various threshold voltages of MOSFETs.

At present, the threshold voltage is mainly modulated by the multi-layer work function metal process. As the size of the transistor shrinks, the area of the gate work function metal stack is getting smaller and smaller. When the multi-layer work function metal is used to modulate the threshold voltage,–the gate resistance will be increased and–the operating speed of devices will be reduced. Therefore, the dipole layer process has been introduced recently to modulate the threshold voltage. The dipole layer is formed by doping other elements into hafnium oxide, such as Aluminum and Lanthanum. Due to the difference in the interfacial oxygen density, the dipoles will be formed at the interface of the oxide layer, thereby modulating the threshold voltage.

This dissertation will focus on the performance and reliability of SiC MOSFETs, silicon carbide junction barrier schottky diodes (SiC JBS) and dipole MOSCAP. The first part discusses the negative bias voltage reliability (NBS) of SiC Junction Barrier Schottky. Power diodes are mainly used as switching and rectifier components. The most important parameters are breakdown voltage, reverse bias leakage and reverse recovery time, which affect the performance and power consumption of components, respectively. Schottky diodes is often used for rectifying and freewheeling because the reverse recovery time is short, which is suitable for high-speed switching. However, the reverse leakage od schottky diode is large, which results in extra power consumption. Junction barrier schottky is a structure which contains low reverse recover time (Trr), low reverse bias current (I_R) and high breakdown voltage (V_{BD}), so this structure is mostly applied in silicon carbide power diodes. SiC JBS is currently a very popular component with high V_{BD} (up to 12000V), low Trr, low I_R and high thermal stability. There have been many studies on its related characteristics and reliability, but few on the reliability mechanism. This paper finds that under the reverse bias reliability, the V_{BD} of SiC JBS increases significantly, so this phenomenon will be studied.

The second part discusses the physical mechanism of reverse bias voltage reliability (NBS) of SiC MOSFETs. Although SiC MOSFETs have been commercialized in large quantities, reliability is still an important issue, especially the gate bias voltage reliability, among which the NBS is the most serious. Because the defects in the interface or gate oxide are easily formed by the carbon clusters which are produced in the process of gate oxidation on SiC MOSFETs. The defects result in the degradation of carrier mobility and the instability of threshold voltage (V_T). This study analyzes the difference in the mechanism of positive bias gate stress (PBS) and negative bias gate stress (NBS) and further analyzes the physical mechanisms of NBS.

The third part discusses the gate positive bias temperature instability (PBTI) reliability of Dipole MOSCAPs. It is found that doping a dipole at the bottom of hafnium oxide increases the gate capacitance and reduces the gate leakage, but the degradation of reliability on the dipole doped MOSCAP is more serious, which may be the injection of electrons or the generation of defects in the oxide layer. The serious degradation is due to the energy band bending caused by the dipole. Under the positive bias, electrons tunneling into the hafnium oxide layer will have greater kinetic energy, which generates the electron injection and the defect generation in the dipole doped device more easily. In addition, the time-dependent dielectric breakdown (TDDB) test is used to verify the degradation of the device.

Keywords: Power Semiconductor devices, Silicon Carbide, SiC MOSFET, SiC JBS, Dipole Dopped MOSCAP

Contents

Figure Captions

Chapter 1

Table Captions