



國立中山大學材料與光電科學學系

博士論文

Department of Materials and Optoelectronic Science

National Sun Yat-sen University

Doctoral Dissertation

氧化鈺摻雜鋇之鐵電記憶體物理機制研究

Investigation on the Physics Mechanism of Zr:HfO₂ Ferroelectric

Memory

研究生：陳穩仲

Wen-Chung Chen

指導教授：蔡宗鳴 博士

Dr. Tsung-Ming Tsai

中華民國 112 年 1 月

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Investigation on the Physics Mechanism of Zr:HfO₂ Ferroelectric Memory

於中華民國 111 年 12 月 11 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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摘要

隨著大數據、人工智慧及物聯網等科技蓬勃發展，電子產品的運算速度及數據存取能力日益受到重視，因此高效能運算晶片及記憶體儲存元件的開發是勢在必行。氧化鈣基底 (HfO_2 -based) 鐵電記憶體 (Ferroelectric Random Access Memory, FeRAM) 與傳統鐵電材料 $\text{SrBi}_2\text{Ta}_2\text{O}_9$ (SBT) 或 $\text{Pb}(\text{ZrTi})\text{O}_3$ (PZT) 相比，寫入速度快、穩定性高、可微縮性高且與半導體製程匹配。然而， HfO_2 基底的鐵電記憶體目前仍存在幾項瓶頸，包含操作電壓過高、記憶窗口不足及操作前需多次喚醒 (wake up)。

本研究為了解氧化鈣基底鐵電記憶體的傳導機制並了解缺陷對鐵電記憶體的影響，針對不同製程溫度的鐵電薄膜與不同電極製備的鐵電記憶體做比較，透過材料分析與電性量測，建立鐵電記憶體的物理模型，進一步設計出高性能與高可靠度的鐵電記憶體。

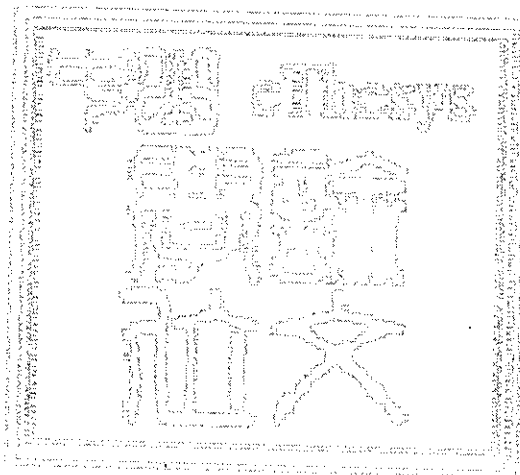
在第三章中，針對鐵電記憶體元件結構成分進行材料分析，搭配電性量測分析鐵電記憶體的 I-V、C-V、與 P-V，並透過變溫實驗確認了鐵電記憶體的轉態機制。因為在低電流的情況是不隨溫度變化的 Fowler-Nordheim 穿隧機制，在高電流狀態下為隨著溫度升高電流會變大的蕭特基機制，根據這些實驗結果，提出一個能帶模型解釋這個現象。

在第四章中，針對高溫與低溫原子層沉積製程的鐵電記憶體分析，根據電性與材料分析結果，低溫製程的鐵電記憶體擁有較好的性能，有較大的晶粒，在相同面積下，擁有大晶粒的缺陷較少，極化值高，根據實驗結果，我們提出一個模型解釋這現象。

在第五章中，針對半導體製程材料常用的 TiN 與 TaN 電極作為鐵電記憶體的電極分析兩者在性能與可靠度的差異，TaN 比較匹配 HZO 薄膜的晶格常數，因此 TaN 電極的鐵電記憶體在喚醒前有較高的極化值與低漏電流。然而，漏電流在經過喚醒過程後顯著上升，經過電流機制擬和分析出 Poole-Frenkel 傳導機制，根據

這些實驗結果與 TiN 電極的元件做比較提出一個氧空缺的模型解釋。

關鍵字：鐵電記憶體、高性能記憶元件、沉積溫度、電流傳導機制、切換物理模型、晶粒大小



Abstract

With the rapid advancement of technologies like big data, artificial intelligence, and the Internet of Things, the attention of the world has shifted more and more toward the computational power and the data access capabilities of electronic goods. Therefore, the development of high-performance computing chips and memory storage devices is imperative. Compared to traditional ferroelectric materials, such as $\text{SrBi}_2\text{Ta}_2\text{O}_9$ (SBT) or PbZrTiO_3 (PZT), the HfO_2 -based ferroelectric random access memory (FeRAM) owns a smaller switching voltage, high writing speed, high stability and high shrink ability and is compatible to the usual semiconductor fabrication process as well. However, the HfO_2 -based FeRAM still exhibits some bottlenecks, including higher operation voltage, insufficient memory windows and the wake-up process needed before operation.

In this study, in order to understand the conduction mechanism of hafnium oxide-based ferroelectric memory and the influence of defects on ferroelectric memory, the characteristics of ferroelectric memory with ferroelectric films at different temperatures or with different electrodes are compared. A physical model of ferroelectric memory is established through the material analysis and the electrical measurements, and ferroelectric memory with high performance and high reliability is further designed.

In Chapter 4, the material analysis is performed for the structure confirmation of ferroelectric memory, and the electrical measurements including current-voltage (I-V), capacitance-voltage (C-V) and polarization-voltage are taken to analyze the ferroelectric memory. Also, the experiments are conducted at various temperatures to help verify the transport mechanism. The low current transport by the F-N tunneling mechanism does not change with temperature, whereas the high current transport via the Schottky mechanism increases with temperature increasing. According to these experiments, a band model is proposed to explain the electron transport in the HZO ferroelectric memory.

In Chapter 5, the ferroelectric memory is fabricated at high and low temperatures in the atomic layer deposition (ALD) process. It is known from the electrical and material analyses that the LTD-FeRAM exhibits better performance and larger grains. Within the same area of the device, therefore, the larger grain would have fewer grain boundaries to cause a smaller number of charge defects. According to the experiments, a model is proposed to explain this phenomenon.

In Chapter 6, this study investigates the difference in electrical performance and reliability with either TiN or TaN applied. Both are commonly used in semiconductor process materials, as the electrode material in ferroelectric random access memories with the same ferroelectric layer of $\text{Hf}_{0.5}\text{Zr}_{0.5}\text{O}_2$ (HZO). Because the lattice constant of TaN is better matched to HZO, the TaN-electrode device possesses larger remnant polarization, higher capacitance and lower leakage before the wake up. However, the leakage current of the TaN-electrode device increases significantly after the wake up. To figure out this phenomenon, current fitting is implemented. The results indicate that electrons of the TaN-electrode device conduct through the oxygen vacancies by Poole-Frenkel emission. Based on these experimental results, an oxygen vacancy model is proposed to compare with the TiN electrode devices.

Keywords: Ferroelectric Memory, High Performance Memory Device, Deposition Temperature, Current Conduction Mechanism, Switching Physics Model, Grain Size

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