氮化鎵磊晶層之奈米機械特性與陰極螢光分析

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摘　　要

氮化鎵在三五族寬能隙半導體材料中，具有直接能隙、低啟動電壓及高亮度等特性，廣泛運用在藍綠光發光二極體、半導體雷射及光學探測器等光子元件中。然而在氮化鎵磊晶層中，因為與基材的晶格不匹配性以及薄膜的熱儲存效應皆會造成的高密度穿越差排以及殘留應力，都會影響其發光效能。因此，本研究藉由了解氮化鎵磊晶層之基礎物理機械特性，期望為後起之研究建立科學性的基礎。

本文利用奈米壓痕試驗與陰極螢光量測探討氮化鎵磊晶的彈塑性變形機制。在實驗中使用有機金屬化學氣相磊晶系統分別在 A 軸向與 C 軸藍寶石基材上生長高品質的氮化鎵磊晶層。首先使用原子力顯微鏡觀察氮化鎵磊晶層經由奈米壓痕試驗所產生的壓縮破壞與變形，發現在壓痕破壞區附近並沒有裂痕的產生。因此在負載與卸負載曲線中所顯示的裂斷(pop-in)現象說明奈米壓痕探針與內部穿越差排在壓痕變形區內交互作用，而在壓痕探針破壞區內，由剪切應力的快速堆積造成氮化鎵磊晶層的塑性變形。氮化鎵磊晶層相異方向的晶格滑移系統造成不同的裂斷與變形現象。

在針對 A 軸向氮化鎵磊晶層使用奈米壓痕探針施予反覆負載破壞中發現，多次反覆負載會造成氮化鎵磊晶層產生局部加工硬化的情形，使得硬度與彈性模數呈現上升的情形，負載過程中所造成的變形與晶格滑移系統有直接的關係。因此，使用陰極螢光系統觀察壓痕破壞區之激發光特性，由結果得知在多次反覆負載破壞下，晶格破壞會沿著滑移系統延伸至壓痕破壞區周圍。

最後，運用奈米刮痕系統探討不同軸向氮化鎵磊晶層之奈米磨潤特性，並使用原子力顯微鏡觀察表面形貌。由研究結果得知，不同軸向的氮化鎵磊晶層呈現相異的彈塑性變形機制，在相同的刮痕破壞方式下，C 軸向氮化鎵磊晶層比 A 軸向具有更好的剪切力抗性。其原因在於相異的晶格滑移系統造成不同的磨潤特性，C 軸向氮化鎵磊晶層較 A 軸向具有較好的奈米機械特性。

關鍵字：機械特性、奈米壓痕、奈米刮痕、彈塑性變形、陰極螢光

The Study of Nanomechanical and Cathodoluminescence Characteristics on the GaN Epitaxial Layers

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Abstract

Gallium nitride (GaN) is III-V wide-band-gap semiconductor and potential candidate for the application of photonic devices in blue/green light emitting diodes (LED), semiconductor lasers, and optical detectors. In terms of GaN film, the mismatch of lattice constants and thermal expansion coefficients in this heteroepitaxy induce high dislocation densities and high level of residual strain in the post growth of thin film, which affects its luminescence efficiency. Therefore, the goals of this thesis are to understand the physics phenomenon found in the GaN films and to establish a scientific basis on the new route for future studies.

This purpose of is to study the elastic–plastic deformation mechanism during nanoindentation experiment and cathodoluminescence test of the GaN films. In the experiment, metal-organic chemical vapor deposition (MOCVD) was employed to deposit high quality GaN on A- and C- axis sapphire substrate. Firstly, the GaN films has been investigated in the pressure-induced impairment events from nanoindentation technique and, the relative deformation effect was observed from atomic force microscopy (AFM). From the morphological studies, it is revealed that none of crack was found even after the indentation beyond the critical depth on the residual indentation impression. The 'pop-in' event during loading-unloading curve, especially lead to deviations in the penetration depth versus indentation load curves was explained by the interaction of the deformed region, produced by the indenter tip, with the inner threading dislocations in the GaN films. The plastic

deformation associated with the individual movement of a small number of large shear stress is quickly accumulated underneath the indenter tip. The extensive interactions between the dislocations slipping along the GaN surface, therefore, confined the slip bands resulted in a 'pop-in' event due to the deformed and strain-hardened lattice structure.

Secondly, Berkovich nanoindentation was used to explore the repetition pressure-induced impairment of the GaN film. The observation of load-displacement vs stress-strain curves concludes that basal slip is implicated in the deformation on the A plane GaN. The increase in the hardness (H) and elastic-modulus (E) was determined from cyclic nanoindentation, and resulted in a crack due to the formation of incipient slip bands and/or the to-and-fro motion of mobile dislocation. It is indicated that the generation of individual dislocation and residual deformation of the GaN films are shown by cathodoluminescence mapping analysis. From the morphological studies, it is revealed that the crack was found by means of AFM technique at nine loading/reloading cycles even after the indentation beyond the critical depth on the residual indentation impression.

Finally, the GaN films on c- and a-axis sapphire substrates and then used the nanoscratch technique and AFM to determine the nanotribological behavior and deformation characteristics, respectively. The AFM morphological results revealed that pile-up phenomena occurred on both sides of the scratches formed on the GaN films. It is suggested that cracking dominates in the case of GaN films while ploughing during the process of scratching; the appearances of the scratched surfaces were significantly different for the GaN films on the c- and a-axis sapphire substrates. In addition, compared to the c-axis substrate, higher values of the coefficient of friction (μ) and deeper penetration of the scratches on the GaN a-axis sapphire sample with the ramped force at 4000 μN was obtained. This discrepancy suggests that GaN films grown on c-axis sapphire have higher shear resistances than those formed on a-axis sapphire. The occurrence of pile-up events indicates that the generation and motion of individual dislocation, which we measured under the sites of critical brittle transitions of the scratch track, resulted in ductile and/or brittle properties as a result of the deformed and strain-hardened lattice structure.

Keywords ： Mechanical properties, Nanoindentation, Nanoscratch, Elastic–plastic deformation, Cathodoluminescence.

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