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学位論文題目	Study on Performance Improvement of GaN-based Light Emitting Diodes Grown on Silicon (111) Substrate （シリコン(111)基板上窒化ガリウム系発光ダイオードの特性改善に関する研究）	
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論文内容の要旨

This dissertation describes the study on the material characterization, fabrication, and evaluation for GaN-based light emitting diodes (LEDs) grown on silicon (111) substrate.

In the chapter 1 to 3, the research background, epitaxial growth of MOCVD, and characterization for the material and LED, including some basic theories for the optical semiconductor device have been presented, respectively. It is known that the high quality GaN grown on Si is difficult to be achieved, which can be contributed to the large tensile stress induced by the lattice mismatch of 17% different thermal expansion coefficients of 116% and between GaN and Si substrate. In particular, during the cooling to room temperature, it often results in the cracks on the surface and the high threading dislocation density (TDD) in the layers, these are useless for device applications. Especially, these problems are the major obstacle to realize high performance GaN-based LEDs grown on Si(111) substrate. For example, the high TDD quickly degrades the LEDs lifetime, which is critical for application in commercial products. On the other hand, large substrate bowing is also the origin of cracks in the epitaxial layer. In order to obtain crack free layer, which has limited the n-GaN layer thickness with the maximum value of 2 μm in the LEDs structure of this study.

In the chapter 4, the GaN-based LEDs on Si substrate by using 3C-SiC as an intermediate layer (IL) have been demonstrated. The effect of 3C-SiC IL on the characteristics of LED has been investigated. The addition of 3C-SiC IL has resulted in the improved GaN crystalline quality, the better interfaces between the buffer and the initial SLS layers, and the smoother morphology of sample surface. As a consequence, the device with 3C- SiC IL showed an enhanced light output power by a factor of 2.4 at a drive current of 20 mA. The superior device performance was attributed to the improvement in the structural properties, which were clarified by AFM, XRD, and TEM measurements. This study implies that using 3C-SiC as IL is one of the effective approaches for enhancing the light output power of LEDs grown on Si substrate. It will also be of interest for a further study of GaN-based optoelectronic device grown on Si.

In the section 5.2 of chapter 5, the GaN-based LEDs grown by metal-organic chemical vapor deposition on 4-in. Si(111) substrates have been demonstrated. The structural property has been revealed by the measurement of X-ray diffraction. One of the full widths at half maximum of ω-scans of the GaN (0002) reflection is around 630 arcsec. Also, it can be found that the GaN epitaxial quality can be improved by increasing the thickness of n-GaN. The device properties have been evaluated through current-voltage, electroluminescence, and light output power-current measurements. As the n-GaN thickness increases from 1 to 2 μm, the light output powers of the LEDs have enhanced approximately two times under the injection current of 20 mA. Moreover, the maximum values of respective external quantum efficiency are achieved as 0.3 and 0.6%, respectively.

Finally, in order to understand the strain and lattice constant evolution in GaN-based LEDs with different n-GaN thickness, lots of characterization measurements have been performed, such as Raman and XRD. These descriptions have been shown in the chapter 6. Three samples with a respective n-GaN thickness of 0.5, 1.0 and 2.0 μm have been prepared. Influence of n-GaN thickness on both the epilayer quality and strain in GaN epilayer have been investigated in detail by the corresponding measurements. It is found that when n-GaN thickness increases, the quality of GaN epilayer is considerably improved with a transition from compressive to tensile strain. In this study, some consistent relations regarding the quality and strain of GaN epilayer derived from those measurements have also been discussed. For example, the stress values of the GaN epilayer from Raman results are in agreement with XRD data. All the demonstrations have revealed several important results, which would inspire some device researchers to further improve the performance of LEDs grown on Si substrate. At the same time, these results again clearly imply that, especially for the structure of GaN-based LEDs grown on Si, both the improvement of GaN epilayer quality and modulation of its strain are imperative.

論文審査結果の要旨

本論文は、シリコン(111)基板上の窒化ガリウム系発光ダイオード（LED）における結晶評価及びデバイス作製・特性評価に関する研究内容をまとめたものである。

第1章では本研究の背景及び目的について記述されている。

第2章では、MOCVD法を用いたSi(111)基板上GaN層などの成長方法及び他の基板との比較を説明し、本研究に使用した高温で成長したAlNバッファー層とAlN/GaN超格子構造の概要が記述されている。

第3章では、GaN膜の品質を評価とするX線回折法(XRD)、透過型電子顕微鏡（TEM）法、LEDに関する量子効率等が記述されている。

第4章では、3C-SiC/Si(111)テンプレート上へGaN系LEDを成長し、3C-SiC中間層の効果が述べられている。AFMとXRD及びTEMの評価結果より、3C-SiC中間層を用いるとGaNの結晶品質が改善され、また、下のバッファー層と最初の超格子の界面やサンプルの表面平坦性も改善された。その結果、3C-SiC中間層がないLEDと比較し、3C-SiC中間層を有するLEDは光出力が約2.4倍増加した。

第5章では、MOCVD法を用いて、Si(111)基板上へ成長したGaN系LEDを検証した。GaN(0002)面のXRDロッキングカーブの半値幅の値は630 arcsecになり、また、n-GaNの厚膜化によって、GaNの結晶品質が改善される傾向が見られた。更に、デバイス特性評価では、n-GaNの膜厚が1から2 μmまで増加した場合には、LEDの光出力と最大外部量子効率が約2倍となった。

第6章では、n-GaNの膜厚を1.0、1.5、2.0 μmと変化された試料を用いて、XRDとラマン分光測定を行い、応力や格子定数の変化を考察した。n-GaNの膜厚を増加させると、結晶品質が向上される一方で、圧縮応力から引っ張り応力まで変化し、応力と結晶品質との関係を明らかにした。

第7章では本研究で得られた成果が総括されている。

以上の研究成果は、10編の学術論文として発表されており、シリコン基板上の窒化ガリウム系発光ダイオードに関する重要な知見を与えている。従って、本論文は本学の博士（工学）論文として十分の価値を有するものと認められる。