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Correlation on GaN epilayer quality and strain in GaN-based LEDs grown on 4-in. Si(1 1 1) substrate

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ABSTRACT

GaN-based LEDs with different thickness of n-GaN have been grown on 4-in. Si(1 1 1) substrate by metal–organic chemical vapor deposition. Quality of GaN epilayer has been evaluated by X-ray diffraction (XRD). Strain information in the structure has been directly investigated by means of micro-Raman scattering. It can be concluded that the compressive strain has varied to a tensile one with increasing n-GaN thickness from 0.5 to 2.0 μm. As a result, in a sample with a 2 μm n-GaN thickness, the tensile stress of GaN epilayer was calculated to be 0.44 GPa. Moreover, the strain states of GaN epilayer have been revealed from the variations of its *a*- and *c*-lattice constants, which have been calculated using XRD results. In addition, emission peak shift of GaN epilayer has been confirmed by cathodoluminescence measurement, and light output power of LEDs has also been measured. Nevertheless, some correlations in this study would inspire researcher to design much more reasonable GaN-LEDs structures in future.

1. Introduction

GaN and its related alloys have always been considered as one of the promising materials for applications in optoelectronic and microelectronic devices [1,2]. Since pasted decade, GaN-based light emitting diodes (LEDs) with wide wavelengths of ultraviolet to green range have already been commercially available. These LEDs are normally grown on sapphire, SiC, and GaN free-standing substrates by metal–organic chemical vapor deposition (MOCVD). However, in large scale fabrication, those substrates are limited due to their small size and high price. In order to overcome this limitation, growth of LEDs on highly conducting 4- to l2-in. silicon (Si) substrates has been suggested as one of the most effective concepts in recent years. In addition, the potential cost reduction by successful growth of GaN-based LEDs on the larger Si substrates is considered to give solid state lighting a boost towards replacing incandescent light [3]. Moreover, choosing Si substrate can also offer numerous advantages, such as good thermal conductivity, simplicity in processing, and possibility of the integration of Si electronics on the same chip [4].

Meanwhile, the biggest challenging issue in terms of GaN epitaxial growth on Si is to relieve the tensile strain, which is caused by the large mismatch in lattice constants (17%) and difference in the thermal expansion coefficients (56%) between the GaN layer and Si substrates [2]. The tensile strain usually leads to emergence of cracks and a high threading dislocations

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(TDs) density by a magnitude of 10^9–10^{11} cm^{-2} at layer thicknesses exceeding 1 μm [5,6]. Actually, our group and others have demonstrated growth of LEDs on Si [2–10]. LEDs with common structures have been grown almost entirely on the 2-in. Si substrates until now [4–6,8–13], except for few groups who have employed 6-in. Si substrates [3,7]. The growth of thicker epitaxial GaN layers will be much more difficult because of the larger strain with increasing size of Si substrate. At the same time, it would further result in a bigger value of curvature and induce some cracks.

Fortunately, the induced strain during growth can be controlled by careful tuning using some novel growth technologies. Recently, a lot of approaches have been attempted to modify the strain and minimize the cracks, such as using AlN/GaN multilayers with a thin AlN/AlGaN buffer layer [2,4], the insertion of AlGaN/GaN superlattice structure [11], employing low-temperature AlN and Si_xN_y interlayer [6,12], and others [8,9,13,14]. Therein, it should be noted that the main purpose of the above methods is to improve the GaN epilayer quality, which directly determines the LEDs performance. Therefore, understanding the quality and strain evolution of GaN epilayers is significantly important for designing the device structure. Until now, in previous related reports, the investigations of strain have been carried out almost in the bulk GaN structure [15–23]. Moreover, many literatures have been focused on the GaN epilayers grown on sapphire [18–22]. In two cases of using sapphire and Si substrates, the introduced strain form into the GaN films is just opposite upon cooling from a high growth temperature to room temperature. Therefore, it is a significant study to simultaneously analyze the quality and strain of GaN epitaxial layers in the GaN-LEDs grown on Si substrate as demonstrated in very few recent reports [14,23].

In this study, GaN-based LEDs have been successfully grown on 4-in. Si(1 1 1) substrate by MOCVD with variable n-GaN thickness. Influence of n-GaN thickness on crystalline quality and strain of GaN epilayers have been comprehensively investigated by high-resolution X-ray diffraction (HR-XRD), micro-Raman scattering, and cathodoluminescence (CL) measurements. In addition, regarding the quality, strain of GaN epilayer, and light out power of LEDs, some consistent relations derived from those characterizations have also been discussed.

2. Experimental

A commercial MOCVD reactor system (Nippon Sanso SR-4000) was used for the epitaxial growth of InGaN-based multiple-quantum wells (MQWs) LEDs structure. Trimethylgallium (TMG), trimethylaluminum (TMA), trimethylindium (TMIn), and ammonia (NH_3) were used as sources for gallium, aluminum, indium, and nitrogen, respectively. Monosilane (SiH_4) diluted in hydrogen was used as n-type dopant, and the p-type dopant was biscyclopentadienyl magnesium (Cp_2Mg). Prior to the growth of LEDs structure, a buffer layer (BL) consisting of a 5 nm n-AlN layer and a 20 nm n-AlGaN layer was grown at 1030 °C. Then, 100-pair n-AlN/GaN (5/20 nm) strained-layer superlattice (SLS) layers and an n-GaN layer were grown at 1130 °C. Finally, an undoped 10-period MQWs consisted of 4 nm $In_xGa_{1-x}N$ wells and 8 nm $In_yGa_{1-y}N$ barriers at 800 °C, a 20 nm p-AlGaN layer and a 100 nm p^+-GaN cap layer at 1030 °C were grown successively. In total three samples were prepared in this study. And, for comparison, sample A, B, and C represent the sample with an n-GaN thickness of 0.5, 1.0, and 2.0 μm, respectively. The other growth conditions were identical for all samples. The sample schematic structure is shown in Fig. 1.

Both symmetric (0 0 0 2) and asymmetric $(1\,0\,\bar{1}\,2)$ ω-scan rocking curves were performed to characterize the tilt and twist factors in the structural imperfection of epitaxial layers. On the other hand, to confirm the strain states in those samples, micro-Raman scattering (JASCO, NRS-3300) experiments were carried out in a backscattering geometry with a combination of instruments of monochromator, equipped with 2400 lines/mm grating, microscope, and a charger couple device detector cooled by liquid nitrogen. At room temperature, Raman scattering experiments using coherent green laser (λ = 532 nm) as the excitation light, a 100× objective lens was used in the confocal microscope to focus and collect the laser light before and after scattering. Then, the *a*- and *c*-axis GaN epilayer lattice constants of samples were determined by HR-XRD (Philips X'Pert MRD) tripe axis 2θ–ω scans. Finally, CL (Gatan MonoCL4 system) measurements were conducted to analyze

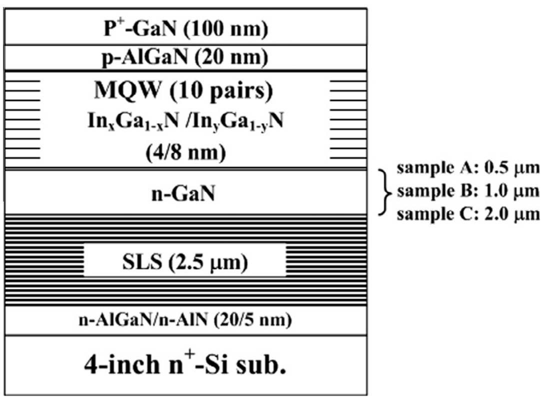

Fig. 1. Schematic structure of the three samples with different n-GaN thickness.