OPTOELECTRONICS AND ADVANCED MATERIALS – RAPID COMMUNICATIONS Vol. 7, No. 1-2, January - February 2013, p. 14 - 17

InGaN/GaN light emitting diodes grow on Si(111) substrates by ammonia flow modulation method

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InGaN/GaN light emitting diodes (LEDs) are grown on Si(111) substrate by metal organic chemical vapor deposition(MOCVD) in this paper. Ammonia (NH_3) flow modulation on SiNx mask layer method was adopted to grow LED structures. Compared with the LED grown by fixing ammonia flow, the sample grown by NH_3 flow modulation shows significant decrease in the full width at half maximum (FWHM). Meanwhile, the device made by ammonia flow modulation method also shows higher electroluminescence (EL) intensity and outpower. The low NH_3 flow in the initial growth stage can considerably increase the GaN island density on the nano-porous SiN*x* layer by enhancing vertical growth. Lateral growth is significantly favored by higher ammonia flow in the subsequent step. This leads to extensive dislocation bending and annihilation, which is also confirmed by transmission electronic microscopy (TEM) characterization. The results show adopting ammonia flow modulation on SiN*x* mask layer is very promising to obtain high power LED on Si substrates.

(Received March 17, 2012; received February 20, 2013)

Keywords: GaN epilayer, MOCVD, Ammonia flow modulation

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1. Introduction

In recent years, the III-nitrides have attracted considerable attention because of the commercial production of high-brightness light emitting diodes (LEDs) [1]. The growth of nitrides on silicon has been of great interest due to the numerous advantages, which include low cost, large-scale availability with high quality, and good thermal and electrical conductivities. Because of the large lattice and thermal mismatch between Si and GaN, growth of crack-free thick GaN on Si(111) posts a great challenge [2,3].

It was found that better crystalline quality could be achieved if the coalescence process was intentionally delayed using either low V/III ratio or relatively high pressure controlling as such the density and size of nuclei in the nucleation layer for GaN growth on sapphire [4,5]. A further reduction of the dislocation density can be obtained by Epitaxial lateral overgrowth methods. Epitaxial lateral overgrowth (ELO) has been proven to be an effective method to reduce dislocations [6,7,8]. It has also been discovered that depositing an in-situ SiN*x* mask with partial coverage of the surface can drastically reduce the dislocation density by termination and bending of threading dislocations [9,10]. However, the growth time of the mask layer must be optimized or incomplete GaN coalescence occurs, resulting in pits on the epilayer and beat the purpose of introducing SiN*x* for dislocation reduction.

In this paper, InGaN/GaN based blue LEDs were grown using fixed and modulated ammonia flow on SiN*x* mask layer were grown on Si(111) substrate. Compared with the sample grown by fixing ammonia flow, the sample grown using the ammonia flow modulation on SiN*x* mask layer shows better structure and optical quality. It was assumed that the low NH_3 flow in the initial growth stage considerably increased the GaN island density on the nano-porous SiN*x* layer by enhancing vertical growth. Lateral growth was significantly favored by higher NH_3 flow in the subsequent step. This led to extensive dislocation bending and annihilation, which was also confirmed by transmission electronic microscopy (TEM) characterization. As a result, improved crystal quality was achieved utilizing NH_3 flow modulation in GaN buffer growth. Meanwhile, the device made by ammonia flow modulation method also show higher EL intensity and outpower. The results show the method using ammonia flow modulation on SiN*x* mask layer is very promising to obtain high power LED on Si substrates.

2. Experiment

The GaN films were grown on 2-inch n-type Si(111) substrates in an Aixtron MOCVD 2000HT system. The Si(111) substrates were cleaned using a standard cleaning procedure before loading into the MOCVD reactor. A 30-nm-thick AlN grown at 1140 °C was used as the seed layer for growing GaN films followed by in-situ SiN*x* mask. Afterwards, two growth methods with different NH_3 flows were adopted to grow undoped GaN layer. For convenience, the sample using the NH_3 modulation and fixed flow method refer to sample A and sample B. Fig.1 displays the schematic samples structure with different growth methods. For sample B, 3.5 slm constant NH_3 flow was adopted during the GaN growth. For sample A, low NH_3 flow (1.5 slm) in the initial growth stage was used in the initial growth stage. Afterwards, the NH_3 flow was increased to 7.5 slm, while the reactor pressure was reduced to 100 mbar. These conditions enhanced lateral growth and favored coalescence of GaN islands. Then, AlN/AlGaN interlayer was then grown, followed by a 1-µm n-GaN layer. After that InGaN/GaN LED structure samples were grown. The MQWs were composed of five periods of InGaN/GaN, the GaN barrier and InGaN well were grown at 950 °C and 810 °C, respectively. And finally a thin undoped spacer and an Mg-doped GaN cap layer were grown on the top. After thermal activation of P-type GaN at 700 °C in an N_2 ambient by rapid thermal annealing (RTA). Top-emitting LEDs with a chip size of 300 µm × 300 µm were fabricated using standard photolithography and dry etch techniques. The standard Ni/Au and Ti/Al alloys were used as p- and n-type contacts, respectively.

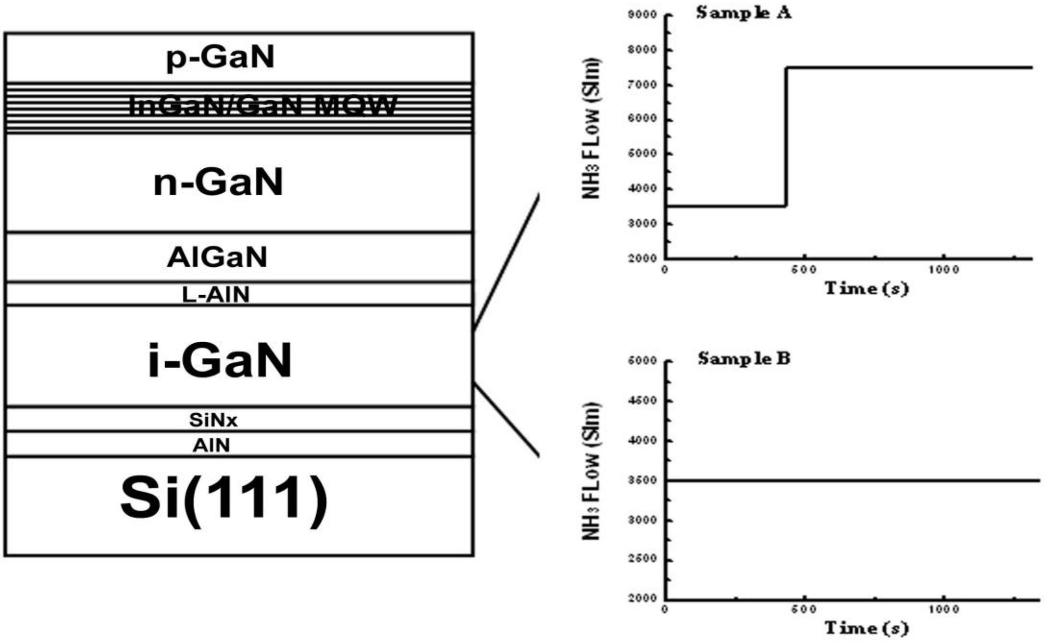

Fig. 1. Schematic samples structure with different growth methods.

The high resolution X-ray diffraction (HRXRD) was performed by Philips MRD system. Transmission electronic microscopy (TEM) was used to observed dislocation evolution. The surface morphologies were observed using Atomic force microscope (AFM). In-situ monitoring of the GaN growth was performed by measuring the reflectivity of the growing wafer with a 600nm wavelength light source. The electroluminescence (EL) and light output power of the unpacked LEDs were measured using the integrated sphere detector.

3. Results and discussion

In-situ monitoring of the GaN growth was performed by measuring the reflectivity of the growing wafer with a 600-nm-wavelength light source. Fig. 2 shows the optical reflectivity traces of GaN growth by different growth method in GaN initial growth on SiN*x* deposition layer.

A 30-nm-thick AlN grown at 1140 ^{o}C was used as the seed layer for growing GaN films. After in-situ deposition SiN*x* layer, GaN initial growth show decrease in reflected intensity that can be attributed to roughening of the surface. The 2D growth mode takes place and we observed regular oscillations with a constant maximum signal. Compared with fixed NH_3 flow method, GaN grown by using the lower NH_3 flow (1.5 slm) in initial stage shows the reflectance signal decreases to zero, which lasts around 1000s. Afterwards, the NH_3 flow was increased to 7.5 slm while the reactor pressure was reduced to 100 mbar. These conditions enhanced lateral growth and favored coalescence of GaN islands. After that, a smooth growing surface could be achieved indicated by the oscillation of the optical reflectivity.

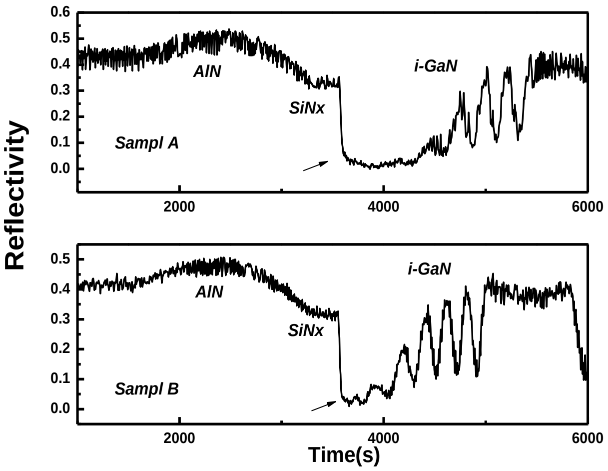

Fig.2. In-situ optical reflectivity measurements for GaN growth by different growth methods. Inset arrow shows epitaxial growth at the initial stage.

Table.1 The full-width at half-maximum (FWHM) of X-ray diffraction of both samples

	FWHM	
Sample	(0002)	(10-12)
Sample A	458 arc sec	504 arc sec
Sample B	516 arc sec	912 arc sec

Measured GaN (0002) and (10-12) ω scan curves from the samples using different growth methods were shown in the Table 1. For the (0002) diffraction (Fig. 2a), the full-width at half-maximum (FWHM) of X-ray diffraction are corresponding to 450 arc sec and 528 arc sec for sample A and sample B. The FWHM of the asymmetric (10-12) diffraction (Fig. 2b) are 624 arc sec and 1008 arc sec for sample A and sample B respectively. The XRD results sample A also is among the best one for crack-free GaN on Si [11]. Thus, for symmetric (0002) and asymmetric (10-12) diffraction, the sample using the varied NH_3 flow growth method shows a narrower FWHM than the one grown by fixed NH_3 flow. It is well accepted that the FWHM of a symmetric diffraction is primarily related to screw-type and mixed threading dislocations and the asymmetric FWHM reflects the information of all types of threading dislocations [12]. Thus it was inferred that lower density of threading dislocations was achieved for the sample grown by using the varied NH3 flow method.

Fig. 3 shows the typical cross-sectional TEM micrograph of sample A. TEM specimen was prepared by first mechanically thinning, and then ion milling with Ar ions to electron transparency. A large number of dislocations were originated from the interface between the AlN buffer layer and GaN, propagated to the surface. However, as the arrow indicates, the bending of dislocations can be clearly observed. Due to the low NH_3 flow in the initial growth stage, which considerably increase the GaN island density. Lateral growth was significantly favored by higher NH_3 flow in the subsequent step. Thus, remarkable reduction of threading dislocations was achieved.

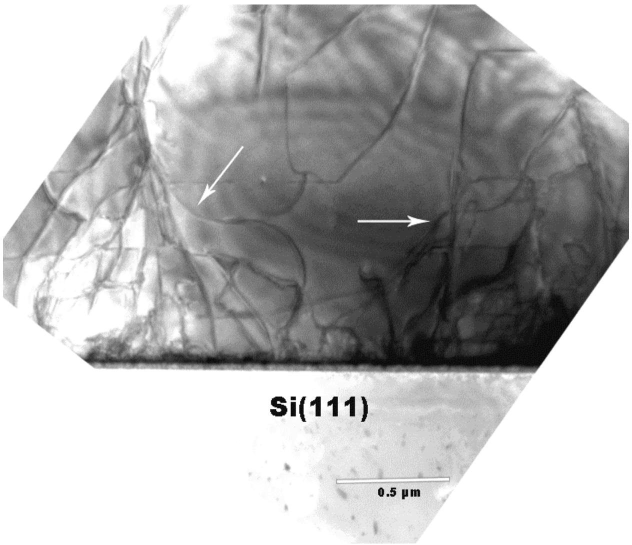

Fig. 3. Cross section transmission electronic microscopy of Sample A.

Fig. 4 displays a comparison of EL spectra of both samples at a forward current of 20 mA. For both samples, the peak emission wavelength is located at 450 nm. Obviously, the sample A shows high EL intensity than that of sample B. And 1.5 times enhancement of emission intensity was obtained for the sample A.

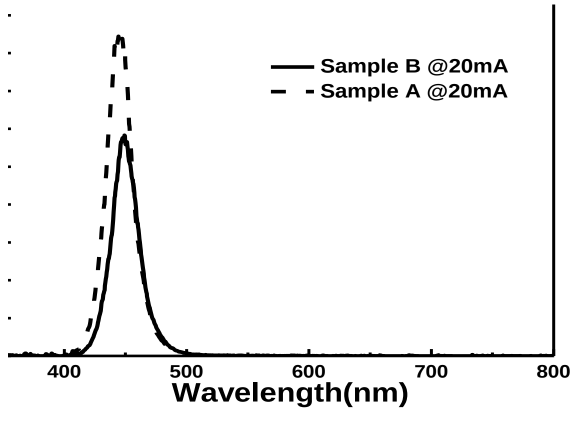

Fig. 4. EL spectra of both samples at a forward current of 20 mA.

Fig. 5 shows the light output power as function of injection current between 0 and 100 mA for two LEDs. The output power intensity of both LEDs increases linearly with the injection current. The output powers for sample A show higher than that of sample B at the same injection current. Meanwhile, under the injection current at 20 mA, 1.5 times relative output power intensity was achieved for sample A.

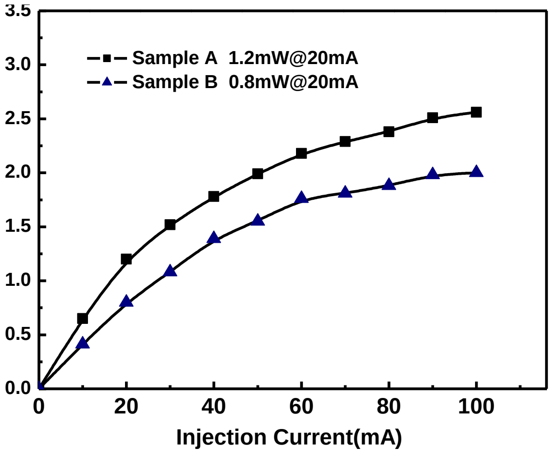

Fig. 5. Light output power as function of injection current between 0 and 100mA for two LEDs.

4. Conclusion

In summary, NH_3 flow modulation on SiN*x* mask layer has been adopted to improve InGaN/GaN based blue LEDs grown on Si(111) substrates by MOCVD. The low NH_3 flow in the initial growth stage considerably increased the GaN island density on the nano-porous SiN*x* layer by enhancing vertical growth. Lateral growth was significantly favored by NH_3 flow in the subsequent step. This led to extensive dislocation bending and annihilation. As a result, improved crystal and optical quality was achieved utilizing NH_3 flow modulation in GaN buffer growth. The EL intensity and outpower of LEDs with NH_3 flow modulation show 1.5 times larger than that of fixed NH_3 flow method. The results show the method adopting NH_3 flow modulation on SiN*x* mask layer is very promising to obtain high power LEDs on Si substrate.

Acknowledgment

This work was supported by the National Natural Science Foundation of China (Grant No. 51102036), Fundamental Research Funds for the Central Universities DC12010207, Program for Liaoning Excellent Talents in University(No. LJQ2012116) and the Opening Project of Chongqing Key Laboratory of Micro/Nano Materials Engineering and Technology (No.KFJJ1205).

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