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High performance GaN-based light emitting diodes grown on 4-inch Si (111)

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1. Introduction

Commercially available GaN-based optoelectronic devices such as light emitting diodes (LEDs) have been grown on sapphire or SiC substrates since the last century [1]. However, silicon (Si) substrate is always attractive for GaN-based devices because of many merits, such as low cost, good thermal conductivity and integration potential in the device fabrication. Nowadays, it is still a challenging issue to grow device-quality GaN epitaxial layers on Si substrate due to the larger mismatch in lattice constants and thermal expansion coefficients [2]. Recently, considerable efforts have been focused on the growth of high quality GaN on Si. For example, it has been reported that using AlN/AlGaN buffer has effectively improved the quality of GaN [3]. In this report, we demonstrate GaN-based LEDs grown by metal organic chemical vapor deposition (MOCVD) using strained-layer superlattices (SLS) on 4-inch Si substrate. LEDs with the maximum output power of more than 1.7 mW are fabricated with the maximum external quantum efficiency of 0.61%. In addition, the high saturation operating current is as high as 280 mA.

2. Experiments

A commercial MOCVD reactor system (Nippon Sanso SR-4000) was used for the epitaxial growth of GaN-based multiple-quantum wells (MQWs) LEDs structure. Trimethylgallium (TMG), trimethylindium (TMIn) and ammonia (NH_3) were used as sources for gallium, indium and nitrogen, respectively. Monosilane (SiH_4) diluted in hydrogen was used as n-type dopant, and the p-type dopant was bis-cyclopentadienyl magnesium (Cp_2Mg). Before 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 ^oC. Then, 100 pair AlN/GaN (5/20 nm) SLS layers and n-GaN layer were grown at 1130 ^oC. Finally, an undoped 10 period MQWs consisting of 4 nm thick $In_xGa_{1-x}N$ wells and 8 nm thick $In_yGa_{1-y}N$ barriers at 800 ^oC, a 20 nm thick p-AlGaN layer and a 100 nm thick p^+-GaN cap layer at 1030 ^oC were grown successively. For comparison, two samples were prepared, in which only n-GaN thicknesses were different. The thicknesses of n-GaN were 2 and 1 μm in sample A and B, respectively. On the other hand, the top-emitting LEDs with a chip size of 500×500 μm^2 were fabricated using a standard process. The details can be referred to our previous report [4]. Figure 1 shows the schematic structure of the LEDs used in this study.

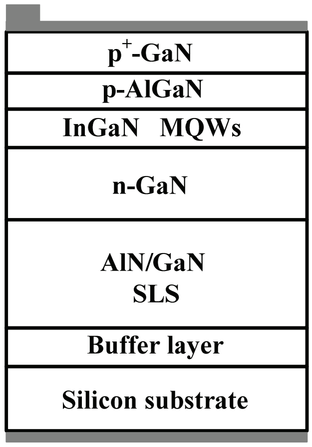

Fig. 1. Schematic structure of GaN-based LEDs

The structural property of Sample A and B was revealed by the measurement of high resolution X-ray diffraction (XRD) (Philips X'Pert Epitaxy). The LEDs were characterized using an on-wafer configuration. The electrical property was measured using a semiconductor parameter analyzer (Agilent 4155C). Also, the optical characteristics were evaluated at room temperature using integrated sphere detector (Otsuka Electronics MPCD-7000).

3. Results and discussion

Figure 2 shows the results of XRD for sample A and B. The full width at half maxmiums (FWHMs) of (0002) are 626 and 1464 arcsec, and those of (10-12) are 916 and 1604 arcsec for samples A and B, respectively. This indicates that there is a significant improvement of GaN epitaxial quality when increasing the thickness of n-GaN.

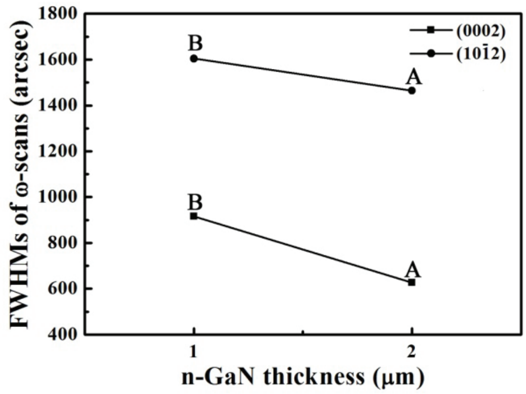

Fig. 2. FWHMs of (0002) and (10-12) of sample A and B

The typical *I-V* characteristics of the two samples are shown in Fig. 3. The operating voltage of sample A and B is 6.1 and 8.0 V at an injection current of 20 mA, respectively.

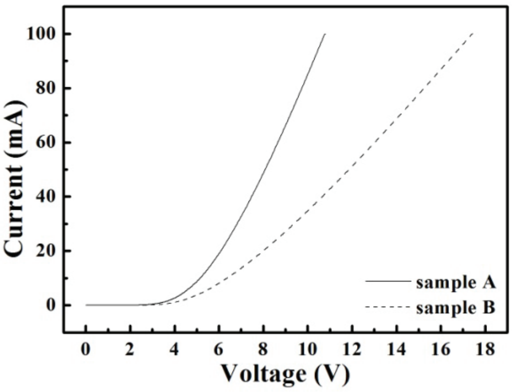

Fig. 3. *I-V* characteristics of sample A and B

Room temperature electroluminescence (EL) spectra of sample A under various currents are shown in Fig. 4. The EL peak is around 490 nm at 20 mA, which corresponds to near band edge luminescence from the optically active regions. In addition, it is interesting to note that a few blue-shifts occur with increasing the current. This is attributed to the free-carrier-screening and band-filling effects [5].

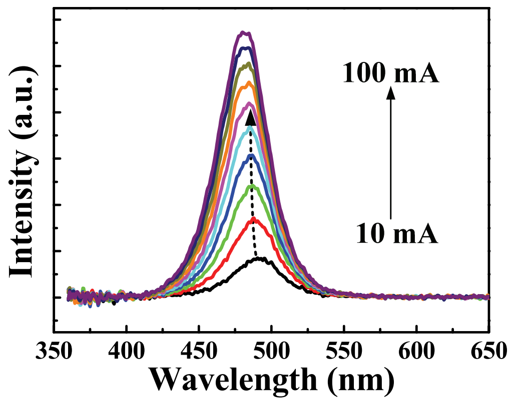

Fig. 4. EL spectra of sample A as a function of injection current!

Figure 5 shows the typical light output power and external quantum efficiency (EQE) versus injection current (L-η_{EQE}-I) characteristics of the two samples. It can be seen clearly that the output power of LEDs increases linearly with injection current initially. However, the output power starts to saturate and finally reaches a maximum, then decreases slightly as the injection current is further increased. It can be observed that the maximum output power of sample A and B is 1.71 and 0.68 mW, respectively. While the saturation operating current of sample A and B is 280 and 170 mA, respectively. From those results, it can be concluded that the optical property of sample A has been improved by increasing the thickness of n-GaN. It is consistent with the results of XRD and *I-V*.

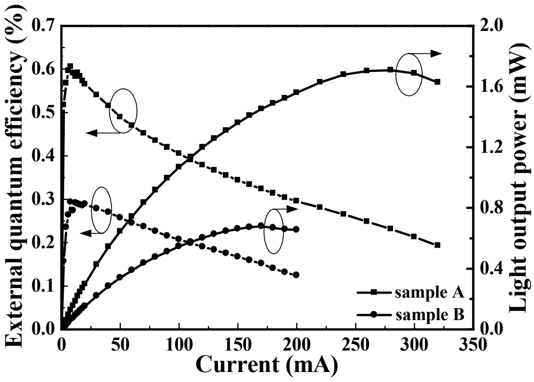

Fig. 5. L-η_{EQE}-I characteristics of sample A and B as a function of injection current

Recently, Li et al. have reported that the maximum output power of GaN-based LEDs grown on Si was about 1.4 mW [6]. Comparing with the same group, it is worth noting that the saturation operating current of sample A is higher by a factor of 1.75. Therefore, it can be speculated that the device with high performance are mainly attributed to the high quality of epitaxial layer and good thermal conductivity of Si substrate. As shown in Fig. 5, we can find that the maximum η_{EQE} of sample A and B is about 0.6% and 0.3%, respectively. These results are well consistent with aforementioned ones. On the other hand, it is also found that the efficiency droop is remarkable, resulting from several factors, such as carrier leakage from the active region, Joule heating from the series and parasitic resistances, high polarization and so on [7].

4. Conclusion

In conclusion, we have demonstrated the GaN-based LEDs grown on 4-inch Si (111) substrate by MOCVD using SLS. It is demonstrated that the performance of GaN-based LEDs can be improved by increasing the thickness of n-GaN. The 1.7 mW output power of LEDs with a high saturation operating current of 280 mA have been fabricated. Consequently, the demonstration has revealed some important results, which can be applied to further improve the performance of LEDs grown on Si substrate in the future.

References

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