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High-Brightness Ultraviolet LEDs on Si Using Quaternary InAlGaN Multi-Quantum-Wells with High Indium Contents

Yasuyuki Fukushima, Yuji Takase, Manabu Usuda, Kenji Orita, Tetsuzo Ueda and Tsuyoshi Tanaka

Semiconductor Device Research Center, Semiconductor Company, Matsushita Electric Industrial Co., Ltd.
1 Kotari-yakemachi, Nagaokakyo, Kyoto 617-8520, Japan
Phone: +81-75-956-9055 E-mail: fukushima.yasuyuki@jp.panasonic.com

1. Introduction

Ultraviolet light emitting diodes (UV-LEDs) have been attracted a great deal of interest as excitation light sources for photocatalyst, solid state lighting or future high density optical data storage systems. III-V nitride is the only viable choice of the material for the UV-LED at present, by which reasonable bright ones have been already reported [1-3]. Aiming at the commercialization, lowering the fabrication cost is the most critical issue. Use of large diameter Si (111) substrates is very promising, however, it has been believed that increase of the emission efficiency of the UV-LEDs on Si (111) should be limited because many dislocations in the order of 10^{10}cm^{-2} would act as non-radiative recombination centers in the conventional AlGaN-based active layers [3,4].

In this paper, we demonstrate bright UV-LEDs on Si (111) using InAlGaN quaternary alloy active layers. The InAlGaN well layers with high In contents up to 10% effectively increase the luminous intensity presumably originated from the localized excitons in the inhomogeneous InAlGaN. The obtained internal quantum efficiency (IQE) of the active layer is as high as 15% at 348nm even on highly defective base layers on Si (111).

2. Structure of UV-LEDs on Si (111)

Figure 1 shows a schematic cross-section of the fabricated the UV-LED on a Si (111) substrate. The epitaxal structure is grown by metal organic chemical vapor deposition (MOCVD), which includes AlN/AlGaN superlattices (SLs) buffer layers and InAlGaN/AlGaN multi-quantum wells (MQW) active layers.

The In mole fraction of the quaternary InAlGaN well layer is varied up to 10% which is higher than the reported values for the active layers emitting UV light [5, 6]. The high In contents would cause localized excitons in the inhomogeneity in the InAlGaN. Note that the well thickness and compositions are designed to emit UV light at around 350nm.

Figure 2 shows the cross-sectional transmission electron microscope (X-TEM) image of the UV-LED structure on Si (111), in which sharp interfaces in the superlattice with the dislocation density of 2×10^{10}cm^{-2} in the overgrown AlGaN are observed.

3. Luminous properties of UV-LEDs on Si (111)

Prior to the LED fabrication, we examine the luminous characteristics of the MQW by photoluminescence (PL) varying the temperatures from 10K to 300K. Figure 3 shows the resultant PL peak intensities as a function of the temperatures. The mole fractions and well thicknesses of the MQW are summarized in Table I. Assuming that non-radiative recombination dose not occur at 10K, the PL intensity at 300K normalized by that at 10K is defined as the IQE of the active layers. The obtained 15% of IQE is as high as that on SiC substrate for the UV emission [5]. In addition, the InAlGaN with 10% of In exhibits inhomogeneous emission as is seen in the monochromatic cathode luminescence (CL) image in Figure 4. The high IQE with inhomogeneous emission implies that the effect of the dislocation is successfully screened by the localized excitons in the inhomogeneous InAlGaN with high In contents.

Figure 5 shows the electroluminescence (EL) spectra of the fabricated UV-LEDs on Si (111) varying the In contents in InAlGaN. The peak intensities are plotted as a function of the In contents in Figure 6. The EL intensity increases as the In content increases, which is consistent with the PL data shown in Fig 5. It is also noted that the structure of the UV-LED dose not contain any GaN layer which could absorb the light with the wavelength shorter than 365nm. Separation of the above LED structure from Si (111) substrate and transferring it to the other substrate with highly reflective electrodes would further enhance the brightness of the UV-LED.

4. Conclusions

In conclusion, we have successfully demonstrate highly-efficient UV-LEDs on Si (111) using InAlGaN quaternary alloy MQW with high In contents up to 10%. The resultant IQE of the active layer is as high as 15% with inhomogeneous emission presumably originated from the localized excitons. The presented LEDs would enable low cost fabrication of the UV emitters to be used in the future applications including photocatalyst system or high density data storage systems.

5. Acknowledgments

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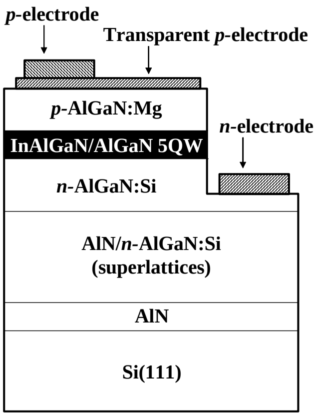

Fig.1. Schematic cross section of InAlGaN/AlGaN MQW UV-LED structure grown on Si (111) substrate.

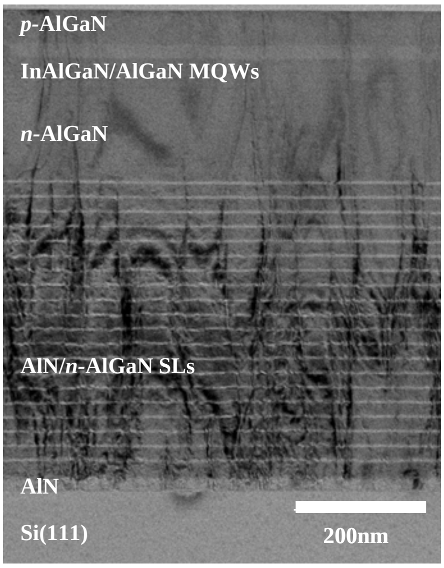

Fig.2. X-TEM of sample (d) InAlGaN/AlGaN MQW UV-LED. The edge dislocation density is $2.0 \times 10^{10} cm^{-2}$.

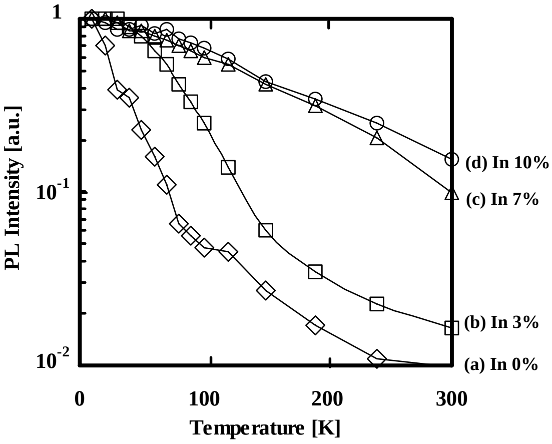

Fig.3. Temperature dependence of the PL intensity from InAlGaN/AlGaN MQW on Si (111) substrates with various In contents of InAlGaN well.

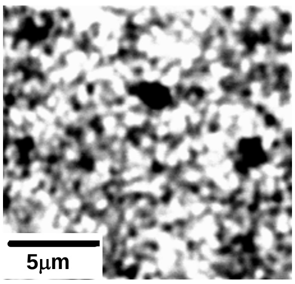

Fig. 4. Monochromatic CL image of Sample (d) at 350nm at room temperature.

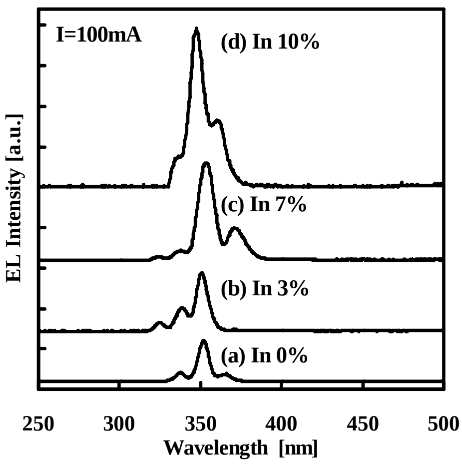

Fig. 5. Room temperature EL spectra of InAlGaN/AlGaN MQW UV-LEDs on Si (111) at the driving current of 100mA with various In contents of InAlGaN well.

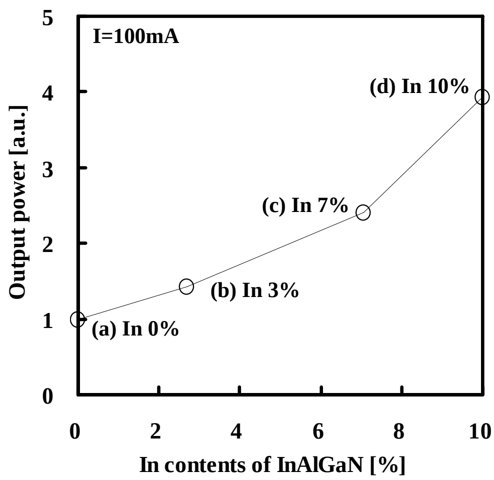

Fig. 6. Room temperature EL intensity of InAlGaN/AlGaN MQW UV-LEDs on Si (111) as a function of the In contents of InAlGaN well.

Table I. Summary of the examined InAlGaN/AlGaN MQW mole fractions and well thickness of the characterized MQW.

	Composition (well/barrier)	Well thickness (nm)	Barrier thickness (nm)	PL peak wavelength (nm)
(a)	$Al_{0.04}Ga_{0.96}N/Al_{0.15}Ga_{0.85}N$	3	10	353
(b)	$In_{0.03}Al_{0.05}Ga_{0.92}N/Al_{0.15}Ga_{0.85}N$	3	10	356
(c)	$In_{0.07}Al_{0.05}Ga_{0.88}N/Al_{0.15}Ga_{0.85}N$	2	10	357
(d)	$In_{0.10}Al_{0.07}Ga_{0.83}N/Al_{0.15}Ga_{0.85}N$	2	10	356