Milliwatt power 270 nm-band 
AlGaN deep-UV LEDs fabricated on ELO-AlN templates

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We demonstrated CW milliwatt power operations of 270 nm-band AlGaN multi-quantum well (MQW) deep-ultraviolet (DUV) light-emitting diodes (LEDs) fabricated on epitaxial lateral overgrowth (ELO) AlN templates on sapphire. An initial AlN stripe layer was grown directly on sapphire by using ammonia (NH\textsubscript{3}) pulse-flow multilayer (ML) growth method. An AlN stripe structure with a width of 5 µm and a spacing of 3 µm was completely coalesced after the growth of an approximately 15 µm-thick ELO-AlN layer grown by low-pressure metal-organic chemical vapor deposition (LP-MOCVD). The edge-type threading dislocation density (TDD) of the wing region of the ELO-AlN layer was \(3 \times 10^8\) cm\(^{-2}\), as observed by cross-sectional transmission electron microscope (TEM) image. The maximum output power of 2.7 mW was obtained from an AlGaN MQW LED with emission wavelength at 273 nm fabricated on ELO-AlN template under room temperature (RT) CW operation.

\textbf{1 Introduction} Recently, the development of high-efficiency 230-350 nm-band deep-ultraviolet (DUV) light-emitting diodes (LEDs) or laser diodes (LDs) has been attracting considerable attentions, because of their wide range of potential applications. AlGaN and InAlGaN alloys are very attractive for realizing high-efficiency DUV-LEDs and LDs [1, 2]. Several groups have reported AlGaN-, InAlGaN-, or AlN-based DUV-LEDs, such as 333–350 nm AlGaN LEDs [3-5], 240–280 nm AlGaN multi-quantum-wells (MQWs) LEDs [6-8], quaternary InAlGaN MQW LEDs [9, 10] and a 210 nm AlN LED [11].

However, the efficiency of AlGaN-based DUV-LEDs with wavelength below 360 nm is much lower than that of InGaN-based blue LEDs. In order to realize high-efficiency AlGaN-based DUV-LEDs, the development of low threading dislocation density (TDD) AlN template is quite important.

We have developed an ammonia (NH\textsubscript{3}) pulse-flow multi-layer (ML) AlN growth method for obtaining low TDD AlN template on sapphire [12]. We have achieved AlGaN- and InAlGaN-based DUV-LEDs with emission wavelength in the range of 222-282 nm by fabricating them on the ML-AlN templates [12-14]. The minimum value of the edge-type dislocation density obtained by the ML-AlN grown on sapphire was \(7 \times 10^8\) cm\(^{-2}\) [14]. Further reduction of TDD is considered to be necessary in order to obtain several tens percent of external quantum efficiency (EQE) for DUV-LEDs or for realizing DUV-LDs.

In order to achieve low TDD AlN or AlGaN templates on sapphire, the use of epitaxial lateral overgrowth (ELO) technique is considered to be quite effective [15]. Meijo university has developed low TDD ELO-AlGaN or AlN buffers on groove-patterned AlN on sapphire [16]. They have achieved 350 nm-band UV-LDs and a 345 nm UV-LED with a high EQE (=6.7%) on the ELO-AlGaN templates [17]. A high crystalline quality ELO-AlN template was also fabricated by using hydride vapor-phase epitaxy (HVPE) [18]. University of South Carolina has reported DUV-LEDs fabricated on ELO-AlN templates [19]. They...
have improved a lifetime reliability in DUV-LEDs by fabricating them on low TDD ELO-AlN [19].

In this study, we fabricated low TDD AlN templates on sapphire substrates by employing an ELO-AlN growth process. We demonstrated CW milliwatt power operations of 270 nm-band AlGaN MQW DUV LEDs fabricated on ELO-AlN templates.

2 Experimental Samples were grown by low-pressure metal-organic chemical vapor deposition (LP-MOCVD). Ammonia, trimethylaluminum (TMAl) and trimethylgallium (TMGa) were used as precursors, with H₂ carrier gas. Figure 1 shows cross-sectional high-resolution scanning electron microscope (HR-SEM) images of (a) an AlN stripe structure and (b) an ELO-AlN template. First, we grew approximately 3.4 μm-thick initial AlN buffer layer directly on sapphire (0001) substrate by using NH₃ pulse-flow multilayer (ML) growth method. The detailed growth method and conditions used for ML-AlN growth were described in references [12] and [13]. The edge dislocation density of the ML-AlN used in this work was approximately 2×10⁹ cm⁻² as observed by cross-sectional transmission electron microscopy (TEM) image. An AlN groove structure was formed along the <11-20> axis on the AlN layer by using an inductive coupled plasma (ICP) etching process.

Figure 1 Cross-sectional high-resolution scanning electron microscope (HR-SEM) images of (a) an AlN stripe structure and (b) an ELO-AlN template.

3 Results and discussions Figure 2 shows a schematic structure of a 273 nm AlGaN QW DUV-LED fabricated on an ELO-AlN template. On the ELO-AlN template, we grew an approximately 2 μm-thick Si-doped Al₈₇Ga₉N buffer layer, 3-layer MQW emitting region consisting of 2 nm-thick Al₄₃Ga₅₃N wells and 7 nm-thick Al₈₇Ga₉N barriers, a 20 nm-thick Mg-doped Al₉₃Ga₇N electron blocking layer (EBL), a 20 nm-thick Mg-doped Al₈₇Ga₉N layer and a 20 nm-thick Mg-doped GaN contact layer. Ni/Au electrodes were used for both n-type and p-type electrodes. The size of the p-type electrode was 300 × 300 μm². The output power radiated to the back of the LED was calibrated using a Si photodetector located behind the LED sample, which was calibrated by measuring luminous flux from LED source by using an integrated-spheres system. All LEDs were measured with bare chip.

The widths of the stripe and the groove were 5 μm and 3 μm, respectively, as seen in Fig. 1. Then, the AlN stripes were embedded by an approximately 15 μm-thick ELO-AlN layer grown at 76 Torr by conventional continuous-flow AlN growth mode. The growth temperature and the V/III ratio used for ELO-AlN growth were 1350°C and 10, respectively. Under these conditions, the growth rate was approximately 6 μm/hour.

The AlN stripes were completely coalesced and embedded to be flat surface after the growth of thick ELO-AlN layer, as can be seen in Fig. 1(b). The full-width at half maximum (FWHM) of the X-ray (0002) and (10-12) ω-scan rocking curves (XRC) of the ELO-AlN template were 336 and 330 arcsec, respectively. The edge-, screw- and mixed-type TDD in the core region (above the terrace area of stripes) evaluated by the cross-sectional TEM images were 8×10⁸, 3×10⁷ and 1×10⁸ cm⁻², respectively. Also, the edge-, screw- and mixed-type TDD in the wing region (above the grooves of the stripes) were 3×10⁸, 0 and 3×10⁷ cm⁻², respectively.
Figure 3 shows electroluminescence (EL) spectra of the AlGaN-MQW DUV LED fabricated on the ELO-AlN template, for the injection current of 80, 120 and 170 mA, measured under room temperature (RT) CW operation. We obtained intense 273 nm emission peak from the LED. The deep level emissions with wavelengths at around 330 nm may correspond to the peak of Mg acceptors. The intensity of the 330 nm sub-peak becomes negligibly small compared with that of main peak for the injection current higher than 200 mA.

Figure 3 Electroluminescence (EL) spectra of the AlGaN-MQW DUV LED fabricated on the ELO-AlN template measured under room temperature (RT) CW operation.

Figure 4 Current vs output power (I-L) and external quantum efficiency (EQE) characteristics of the 273 nm AlGaN-MQW LED measured under RT CW operation.

Figure 4 shows the output power and external quantum efficiency (EQE), \( \eta_{\text{ext}} \), as a function of current of the 273 nm AlGaN-MQW LED measured under RT CW operation. The output power was 2.7 mW with injection current of 700 mA and the maximum EQE was 0.04%, under RT CW operation. We have already obtained an EQE of 0.43% for a 250 nm AlGaN-MQW LED which was fabricated on an ML-AlN template without an ELO-AlN geometry. Therefore, the EQE obtained in this work was much smaller than the EQEs of the previous DUV-LEDs without using ELO-AlN.

The main reason of a significant reduction of EQE in this work is considered to be due to the leakage current induced by the abnormal AlN cores generated on the ELO-AlN layer. We observed a lot of abnormal AlN cores on the AlN-ELO surfaces. Figure 5 shows (a) a bird's-eye view and (b) a cross-sectional image of the abnormal AlN cores generated on ELO-AlN layer observed by HR-SEM. The size and the density of the abnormal AlN core observed on the ELO-AlN layer were approximately 6 μm diameter and \( 10^5 \) cm\(^{-2} \), respectively. We confirmed that polarity inversion occurs for the abnormal AlN cores by the KOH etching method. The EQE of the LED may be significantly improved by eliminating the abnormal AlN nucleation on the ELO-AlN template.

Figure 5 (a) A bird's-eye view and (b) a cross-sectional image of the abnormal AlN cores generated on ELO-AlN layer observed by HR-SEM.

4 Conclusions

In conclusion, we fabricated an AlGaN-QW LED on ELO-AlN with emission wavelength at 273 nm for RT CW operation. The maximum output power of the 273 nm LED was 2.7 mW under RT CW operation.
The EQE obtained in this work was much smaller than the EQEs of the previous DUV-LEDs without using ELO-AlN. The EQE may be significantly improved by eliminating the abnormal AlN nucleation on the ELO-AlN template.

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