227 nm AlGaN Light-Emitting Diode with 0.15 mW Output Power Realized using a Thin Quantum Well and AlN Buffer with Reduced Threading Dislocation Density

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AlGaN multi-quantum-well (MQW) deep-ultraviolet (DUV) light-emitting diodes (LEDs) fabricated on sapphire substrates with emission at 227 nm are demonstrated. A remarkable enhancement in the DUV LED output power was achieved by using a thin AlGaN quantum well only 1.3 nm in thickness, with atomically flat hetero-interfaces, together with an AlN buffer layer of reduced threading dislocation density. The AlGaN-MQW DUV LEDs exhibited single emission peaks. The output power was 0.15 mW with injection current of 30 mA and the maximum external quantum efficiency was 0.2%, under room temperature pulsed operation.

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High-efficiency deep-ultraviolet (DUV) semiconductor light sources with emission wavelengths shorter than 280 nm have potential applications in sterilization, water purification, medicine, and biochemistry. AlGaN is a candidate material for realizing high-efficiency DUV light-emitting diodes (LEDs).

Several groups have reported AlGaN- or InAlGaN-based DUV LEDs, such as 333–350 nm AlGaN LEDs$^{1-3}$ in 1998–2001, 240–280 nm AlGaN multi-quantum-well (MQW) LEDs$^{4-6}$ and quaternary InAlGaN MQW LEDs$^{7-9}$ in 2002–2006. The shortest wavelength AlN LED, at 210 nm, was reported in 2006.$^{10}$ We previously developed 231–261 nm AlGaN QW LEDs using high-quality AlN buffer layers on sapphire.$^{11}$ We obtained cw 1.65 mW output power from a 261 nm AlGaN LED. However, the output power of a 231 nm LED was much smaller.$^{11}$

In AlGaN-based QWs a spatial separation of the electron and hole wave-functions is induced by the large electric field in the well due to polarization along the c-axis of the crystal. However, electron–hole separation is suppressed as the well thickness decreases, and therefore the use of a very thin quantum well is expected to enhance radiative recombination. Moreover, reduction of the threading dislocation density (TDD) leads to a significant increase in the internal quantum efficiency (IQE) of AlGaN QWs.$^{12}$ In this report, we show that the output power of AlGaN DUV LEDs is remarkably improved by reducing the quantum well thickness. We realized an output power of over 0.1 mW in an AlGaN LED at a wavelength shorter than 230 nm by employing a thin AlGaN quantum well and reducing the TDD of the AlN buffer.

The samples were grown on sapphire (0001) substrates by low-pressure metal–organic chemical vapor deposition (LP-MOCVD). The LED layer structures were deposited on a low TDD AlN buffer fabricated using an ammonia (NH$_3$) pulsed-flow multilayer (ML) growth method.$^{11}$ Details of the ML-AlN growth method were described in ref. 11. We used three growth modes in this method. The initial deposition, in order to fabricate an AlN nucleation layer, was performed using an NH$_3$ pulsed-flow growth at 200 Torr and 1300 °C with an average V/III ratio of 60. Following this, migration enhancement epitaxy, used for the coalescence process, was performed using NH$_3$ pulsed-flow growth at 76 Torr and 1200 °C with an average V/III ratio of 750. A high growth-rate (> 6 μm/h) AlN layer was then grown with a conventional continuous flow at 76 Torr and 1200 °C with a V/III ratio of 23. The advantage of the use of a ML-AlN for the DUV LED is that low TDD AlN can be obtained without using AlGaN layers, yielding a device structure with minimal DUV absorption. An AlGaN-free buffer is believed to be important for realizing sub-230-nm band-high-efficiency LEDs.

The total thickness of the ML-AlN buffer was 4.8 μm. The full-width at half maximum (FWHM) of the X-ray (0002) and (1012) ω-scan rocking curves (XRC) of the AlN layer were approximately 220 and 530 arcsec, respectively. The edge-, screw-, and mixed-type dislocation densities of the AlGaN on ML-AlN were 1.8 × 10$^{10}$, 4 × 10$^{7}$, and 9 × 10$^{7}$ cm$^{-2}$, respectively, as determined from a cross-sectional transmission electron microscope (TEM) image.

Figure 1 shows a cross-sectional TEM image of an AlGaN MQW DUV LED fabricated on a ML-AlN/sapphire template. We grew an approximately 1.3-nm-thick Al$_{0.97}$Ga$_{0.03}$N buffer-layer, followed by a 3-layer MQW, consisting of 1.3-nm-thick Al$_{0.79}$Ga$_{0.21}$N wells and 7-nm-thick Al$_{0.87}$Ga$_{0.13}$N barriers, a 21-nm-thick undoped Al$_{0.87}$Ga$_{0.13}$N barrier, a 15-nm-thick Mg-doped Al$_{0.95}$Ga$_{0.05}$N

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Fig. 1. Cross-sectional TEM image of an AlGaN MQW DUV LED fabricated on a ML-AlN/sapphire template.
electron-blocking layer (EBL), a 10-nm-thick Mg-doped Al$_{0.87}$Ga$_{0.13}$N p-layer, and an approximately 20-nm-thick Mg-doped GaN contact layer on the ML-AlN buffer. We used a thin QW in order to obtain a high IQE by suppressing the effects of the polarization field in the well. It is believed to be particularly important to obtain atomically smooth hetero-interfaces to obtain a high IQE from such a thin QW. The atomically flat hetero-interfaces for the 1.3-nm-thick three-layer QWs are confirmed by the cross-sectional TEM image.

The sample geometry used for the LED measurement was the same as that shown in ref. 11. The reported output power values correspond to the total radiant flux from the LEDs. Output power measurements were made using a charge-coupled device (CCD) photodetector system which was calibrated using a reference LED of geometry identical to the measured experimental LEDs. The total radiant flux of the reference LED was known from independent measurements using an integrating sphere.

Figure 2 shows electroluminescence (EL) spectra of the fabricated 227 nm AlGaN-MQW LED, with injection currents of 10, 20, and 30 mA, measured under RT pulsed operation. The emission peak wavelength was 227 nm with the injection current of 30 mA. The applied voltage was 26 V for the current of 10 mA and 42 V for the current of 30 mA.

Figure 3 shows the EL spectra on a log scale of a 227 nm LED, which was fabricated on the same wafer used for the LED shown in Fig. 2. The deep-level emissions with wavelengths at around 255 and 330–450 nm were more than two orders of magnitude smaller than the main peak. These peaks may correspond to deep levels associated with Mg acceptors, or other impurities or defects.

Figure 4 shows the output power and external quantum efficiency (η$_{ext}$), as a function of current for the 227 nm AlGaN-MQW LED, measured under RT pulsed operation. The reported output power values correspond to the total radiant flux from the LEDs. Output power measurements were made using a charge-coupled device (CCD) photodetector system which was calibrated using a reference LED of geometry identical to the measured experimental LEDs. The total radiant flux of the reference LED was known from independent measurements using an integrating sphere.

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Table I summarizes the differences between AlGaN LEDs with emission at around 230 nm in previous work, reported in ref. 11, and in this work. We obtained a dramatic single-peaked operation of the AlGaN-MQW LED. The emission peak wavelength was 227 nm with the injection current of 30 mA. The applied voltage was 26 V for the current of 10 mA and 42 V for the current of 30 mA.

Table I. Differences in the output power, EQE, quantum well thickness, structure of ML-AlN buffer and TDD of AlGaN buffer between AlGaN MQW DUV LEDs in previous work, reported in ref. 11, and in this work.

<table>
<thead>
<tr>
<th></th>
<th>Previous work</th>
<th>This work</th>
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<tbody>
<tr>
<td>Wavelength (nm)</td>
<td>231</td>
<td>227</td>
</tr>
<tr>
<td>Maximum output power (μW)</td>
<td>5</td>
<td>150</td>
</tr>
<tr>
<td>Maximum EQE (%)</td>
<td>0.001</td>
<td>0.2</td>
</tr>
<tr>
<td>Quantum well thickness (nm)</td>
<td>2</td>
<td>1.3</td>
</tr>
<tr>
<td>Repetition step of ML-AlN</td>
<td>2 times</td>
<td>1 time</td>
</tr>
<tr>
<td>Total thickness of NH$_3$ pulsed-flow AlN (μm)</td>
<td>0.6</td>
<td>1.2</td>
</tr>
<tr>
<td>TDD (edge-type) in AlGaN (cm$^{-2}$)</td>
<td>$3.2 \times 10^9$</td>
<td>$1.8 \times 10^9$</td>
</tr>
<tr>
<td>TDD (screw-type) in AlGaN (cm$^{-2}$)</td>
<td>$3.5 \times 10^9$</td>
<td>$4 \times 10^7$</td>
</tr>
</tbody>
</table>

Figure 2 shows electroluminescence (EL) spectra of the fabricated AlGaN-MQW LED, with injection currents of 10, 20, and 30 mA, under room temperature (RT) pulsed operation. The pulse width and the repetition frequency were 3μs and 10 kHz, respectively. We obtained single-
increase in the output power, from 5 μW to 0.15 mW, by reducing both the QW thickness and the TDD of the AlGaN buffer. We have previously demonstrated that the emission efficiency of the 254 nm AlGaN QW was dramatically increased (by more than 50 times) by reducing the XRC (1012) FWHM of the AlGaN buffer from around 1500 to 500 arcsec.12) The dramatic increase in emission efficiency can be explained by the suppression of non-radiative recombination as the mean distance between the TDs becomes greater than the carrier diffusion length in the QWs. Taking this into account, we estimate that the IQE of the QW was increased by at least several times as the edge-type TDD was reduced from $10^9$ to $10^8$ cm$^{-2}$. In addition, the reduction in the screw-type TDD is expected to contribute to the improvement in the emission efficiency.

Figure 5 shows the quantum well thickness dependence of EL spectra of 220–230 nm-band AlGaN MQW DUV LED. Measured at RT Pulsed

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