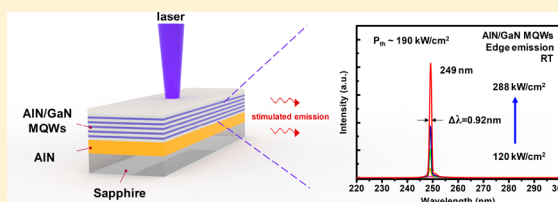


## Deep UV Laser at 249 nm Based on GaN Quantum Wells

Maocheng Shan,<sup>†,‡,||</sup> Yi Zhang,<sup>†,||</sup> Tinh B. Tran,<sup>‡</sup> Jie'an Jiang,<sup>§</sup> Hanling Long,<sup>†</sup> Zhihua Zheng,<sup>†</sup> An'ge Wang,<sup>†</sup> Wei Guo,<sup>§,||</sup> Jichun Ye,<sup>§,||</sup> Changqing Chen,<sup>\*,†,||</sup> Jiangnan Dai,<sup>\*,†,||</sup> and Xiaohang Li<sup>\*,‡,||</sup><sup>†</sup>Wuhan National Laboratory for Optoelectronics, Huazhong University of Science and Technology, Wuhan 430074, People's Republic of China<sup>‡</sup>King Abdullah University of Science and Technology (KAUST), Advanced Semiconductor Laboratory, Thuwal 23955, Saudi Arabia<sup>§</sup>Ningbo Institute of Materials Technology and Engineering, Chinese Academy of Sciences, Ningbo, 315201 Zhejiang, People's Republic of China

**ABSTRACT:** In this Letter, we report on deep UV laser emitting at 249 nm based on thin GaN quantum wells (QWs) by optical pumping at room temperature. The laser threshold was 190 kW/cm<sup>2</sup> that is comparable to state-of-the-art AlGaIn QW lasers at similar wavelengths. The laser structure was pseudomorphically grown on a *c*-plane sapphire substrate by metalorganic chemical vapor deposition, comprising 40 pairs of 4 monolayer (ML) GaN QWs sandwiched by 6 ML AlN quantum barriers (QBs). The low threshold at the wavelength was attributed to large optical and quantum confinement and high quality of the material, interface, and Fabry-Pérot facet. The emissions below and above the threshold were both dominated by transverse electric polarizations thanks to the valence band characteristics of GaN. This work unambiguously demonstrates the potentials of the binary AlN/GaN heterojunctions for high-performance UV emitters.

**KEYWORDS:** deep UV, lasers, AlN/GaN quantum wells, quantum confinement, MOCVD, optically pumped



Deep ultraviolet (DUV) light-emitting diodes (LEDs) and lasers with wavelengths shorter than 280 nm have great potentials in applications including sterilization, communication, optical storage, spectral analysis, and biochemical detection.<sup>1–3</sup> In the past few decades, AlGaIn multiple quantum wells (MQWs) were extensively investigated for DUV emission due to its ultrawide and tunable bandgap via changing the alloy composition.<sup>4–8</sup> Nearly full-spectrum DUV LEDs and optically pumped DUV lasers have been demonstrated based on the AlGaIn MQWs.<sup>9,10</sup> However, the external quantum efficiency (EQE) of the in-production DUV LEDs is still low despite some encouraging laboratory results.<sup>11</sup> Furthermore, due to challenges in carrier injection and mode confinement, electrically injected DUV laser diodes have yet to be demonstrated.<sup>10</sup> One of the factors contributing to unfavorable performance of DUV LEDs and lasers is the quantum confined Stark effect (QCSE) amid the MQW active region which typically employs a few nm thick AlGaIn quantum wells (QWs), reducing the electron–hole wave function overlap and thus the radiative recombination efficiency.<sup>12</sup> In addition, the optical polarization of AlGaIn emission mainly depends on the alloy composition.<sup>13</sup> As the Al composition steps up into the DUV spectrum, the optical polarization of the AlGaIn emission gradually switches from transverse electric (TE) to transverse magnetic (TM) due to the rearrangement of the topmost valence sub-bands of AlGaIn.<sup>14</sup> Because TM-polarized light cannot be easily extracted from the surface of mesa-type devices, the light

extraction efficiency (LEE) of the AlGaIn MQW DUV LEDs is severely compromised.<sup>15</sup> The TM mode is also not as desirable for edge-emitting lasers as the TE mode, because the former suffers higher absorption by the p-type layers and metals due to its wider optical profile along the *c*-axis.<sup>13</sup>

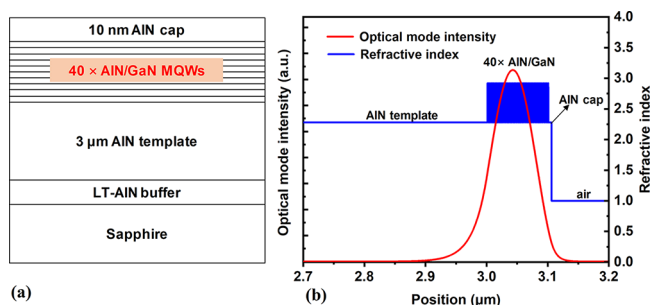
Recently, the AlN/GaN MQWs have emerged as a promising alternative structure for UV emission.<sup>16–22</sup> As the thickness of the GaN QWs reduces to a few atomic monolayers (MLs), extreme quantum confinement occurs that enlarges the effective transition energy by several eV from the bandgap of GaN (~3.3 eV).<sup>17</sup> By merely tuning the GaN QW thickness, spontaneous emissions from 234 (5.3 eV) to 298 nm (4.2 eV) have been demonstrated.<sup>19,23</sup> Also, the spontaneous emission of the GaN QWs exhibited enhanced TE polarization as opposed to that of the AlGaIn MQWs,<sup>16</sup> which can benefit both DUV LEDs and lasers. Additionally, the electron and hole wave function overlap can be greatly improved due to the small QW thickness, despite large heterointerface polarization. However, despite those advantages, only the spontaneous emission has been realized from the AlN/GaN MQWs. To date, there has not been any report of lasing, which, if demonstrated, would truly demonstrate that the potentials of the AlN/GaN MQWs are on par with the AlGaIn MQWs for high-performance DUV emitters.

Received: June 19, 2019

Published: September 20, 2019

In this work, we have demonstrated the DUV laser based on the AlN/GaN MQWs at room temperature (RT) by optical pumping. The laser structure was designed to possess enhanced lateral optical confinement factor and grown on by metalorganic chemical vapor deposition (MOCVD). The structure was characterized by X-ray diffraction (XRD), atomic force microscopy (AFM), and high-resolution transmission electron microscopy (TEM). Power-dependent photoluminescence (PL) experiments were carried out to demonstrate the lasing. Optical polarization of the laser emission below and above the threshold was also studied.

The AlN/GaN MQW laser structure was grown on a two-inch *c*-plane sapphire substrate. With hydrogen as the carrier gas, trimethylaluminum, trimethylgallium, and ammonia were employed as the precursors of Al, Ga, and N, respectively. As shown in Figure 1a, a 15 nm low-temperature (LT) AlN buffer



**Figure 1.** (a) Schematic diagram for the AlN/GaN MQW DUV laser grown on the sapphire substrate; (b) Simulated optical mode profile and refractive index distribution of the laser structure.

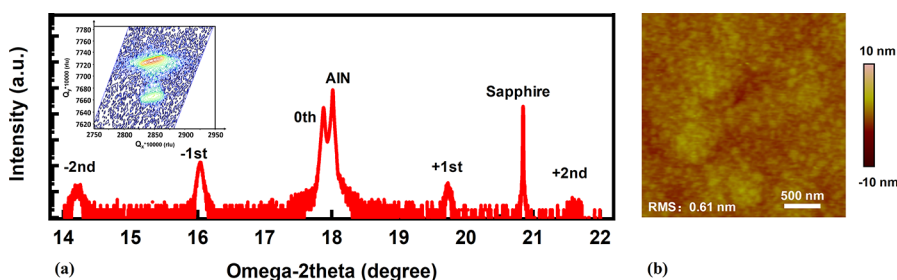
was first grown at 750 °C on the sapphire substrate. Subsequently, a 3 μm AlN template was grown at 1230 °C. The full width at half maximum (fwhm) values of (002) and (102) XRD rocking curves of the template are 85 and 373 arcsec, which are smaller than those of the AlN/sapphire templates used for the AlGaN MQW DUV lasers,<sup>13,24</sup> establishing a high-quality foundation for subsequent growth of the heterostructures. Then the AlN/GaN MQW active region was grown at 1040 °C. This temperature was chosen to ensure that the thin GaN QWs maintain high quality, while they do not evaporate amid the growth, a key to sharp AlN/GaN heterointerface. The thicknesses of the GaN QWs and the AlN QBs were designed to be 4 MLs and 6 MLs, respectively. The comparable thicknesses between the GaN QWs and the AlN QBs can lead to larger average index, as opposed to the MQWs whose AlN QBs are much thicker than the GaN QWs.<sup>21,25</sup> Furthermore, the MQW pair number of 40 was selected due to comprehensive considerations of the lateral

optical confinement, penetration depth of the excitation laser beam, gain medium volume, strain relaxation, and material and interface quality. Finally, a 10 nm AlN cap was deposited as the surface passivation layer. Ideally, the AlN cap layer should be thicker to form a symmetry waveguide. However, a thicker AlN cap would considerably absorb the pumping laser energy from the ArF excimer laser ( $\lambda = 193$  nm) utilized in this study. The optical field distribution of the laser structure was calculated by the COMSOL Multiphysics software package with indices illustrated in Figure 1b. Although there was mode leakage because of the asymmetric waveguide, maximum optical field was located near the center of the MQW active region leading to a large optical confinement factor of 35.4%. The large factor was partially attributed to the use of high-index GaN QWs and large MQW pair number of 40. Also, it is partially caused by the comparable thicknesses between the GaN QWs and the AlN QBs, resulting in a larger average index.

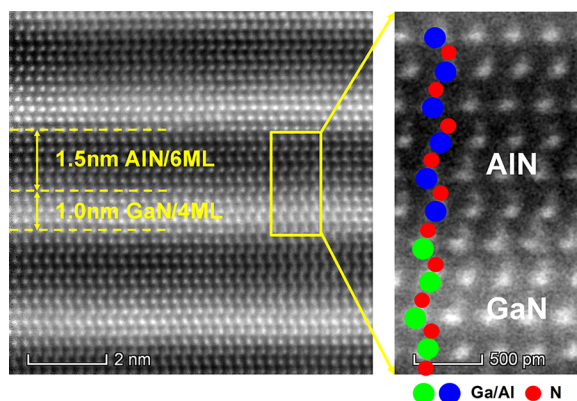
The XRD  $\omega$ -2 $\theta$  scan was performed to probe the MQW superlattice. As shown in Figure 2a, higher-order satellite peaks were observed, indicating a periodic structure with sharp heterointerfaces. The XRD asymmetric (105) reciprocal space mapping (RSM) manifests that the AlN/GaN MQWs were grown pseudomorphically on the AlN/sapphire template. In Figure 2b, the surface morphology of the as-grown wafer was characterized by AFM, showing low RMS roughness of 0.61 nm and no obvious surface defects. Because the MQWs are close to the surface, the low RMS roughness agrees with the satellite peaks of the XRD  $\omega$ -2 $\theta$  scan.

To further investigate the AlN/GaN MQWs, especially the heterointerface and the layer thickness, high-angle annular dark-field (HAADF) scanning transmission electron microscopy (STEM) experiments were carried out. The sample was prepared using the focused ion beam (FIB) technique and then loaded into an FEI Themis Z TEM system for cross-sectional imaging along the  $[1-100]$  zone axis at 300 keV. As shown in Figure 3, the GaN QWs and the AlN QBs are represented by the brighter and darker lateral stripes that exhibit distinct interfaces with uniform thickness, agreeing with the XRD results (Figure 2a). The GaN QWs and the AlN QBs comprise 4 MLs (1.0 nm) and 6 MLs (1.5 nm), respectively, which is consistent with the epitaxial design.

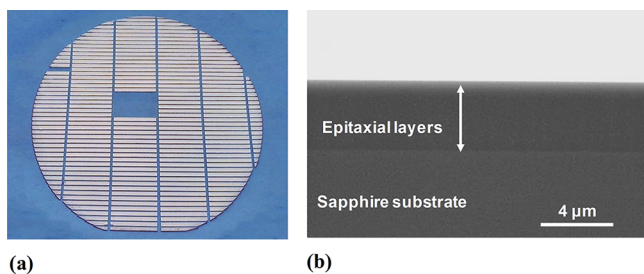
To fabricate the edge-emitting laser cavity for optical pumping, the sapphire substrate was first thinned from the backside. Then the laser scribing was applied. Afterward, the laser bars were cleaved along the *m*-plane of the epitaxial layers with a cavity length of 1 mm. The cleaved laser bars from the two-inch wafer are shown in Figure 4a. The cavity facets were examined by the cross-sectional SEM, showing high smoothness in Figure 4b. No additional dielectric mirrors were deposited in this study. The optical pumping experiment was



**Figure 2.** (a) XRD  $\omega$ -2 $\theta$  scan with the inset being the asymmetric (105) RSM and (b)  $3 \times 3 \mu\text{m}^2$  AFM image of the as-grown laser wafer.



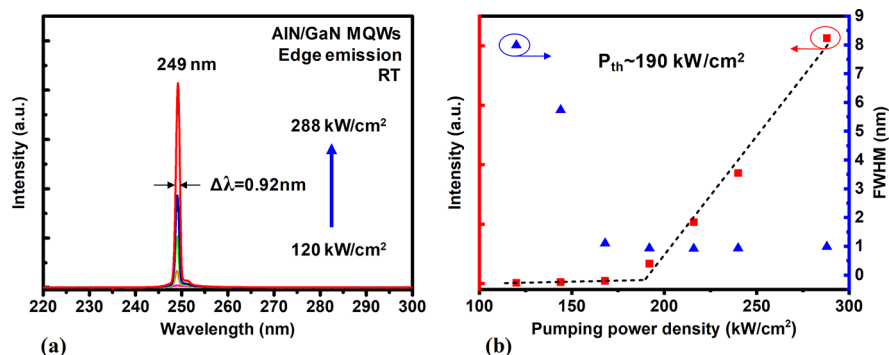
**Figure 3.** Cross-sectional atomic-resolution HAADF-STEM images of the AlN/GaN MQWs.



**Figure 4.** (a) Photograph of the cleaved laser bars and (b) a cross-sectional SEM image of the cleaved facet.

carried out using an ArF excimer laser with a pulse width of 5 ns and a repetition frequency of 50 Hz at different power densities and at RT. The edge emissions were collected near one facet using a Horiba iHR550 spectrometer and a cooled charged-coupled device. The optical polarizations were measured perpendicular to the *c*-axis by employing a Glan-Taylor polarizer between the optical fiber and the laser facet.

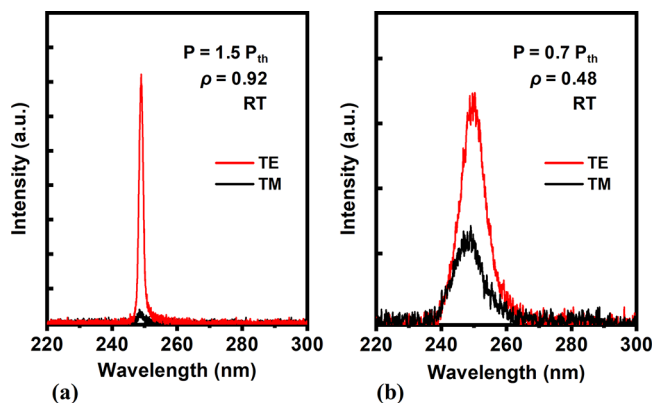
Figure 5a shows the PL spectra with various pumping power densities from 120 to 288 kW/cm<sup>2</sup>. The peak emission wavelength was 249 nm, and there was almost no wavelength shift between spontaneous and stimulated emissions, indicating the minimized QCSE, thanks to the thinness of the GaN QWs. The short wavelength of 249 nm, equivalent to the transition energy of 5.0 eV, suggests the extreme quantum confinement effect in the AlN/GaN QWs. The intensity versus the pumping power density (red squares) in Figure 5b demonstrated the lasing operation with a low threshold of 190 kW/cm<sup>2</sup>, comparable to the state-of-the-art DUV lasers based on



**Figure 5.** (a) Laser emission spectra and (b) peak intensity and line width of the spectra as a function of pumping power density.

AlGaN MQWs grown on sapphire and AlN substrates at similar wavelengths.<sup>3,13,26</sup> Such a threshold can be mostly attributed to the high material and interface quality, large quantum and optical confinement, and smooth cleaved facet. The spectral fwhm (blue triangles) decreased significantly from 8 to 0.92 nm as the pumping power density reached the threshold, reaffirming the lasing operation.

The optically polarized emissions of the laser above and below the threshold are shown in Figure 6a and b, respectively.



**Figure 6.** TE- and TM-polarized emissions of the laser at pumping power densities *P* (a) above the threshold ( $P = 1.5P_{th}$ ) and (b) below the threshold ( $P = 0.7P_{th}$ ).

The degrees of polarization ( $\rho$ ), defined as  $\rho = (I_{TE} - I_{TM}) / (I_{TE} + I_{TM})$ , are 0.92 and 0.48 for Figure 6a and b, respectively. Therefore, the laser emission above the threshold was nearly pure TE-polarized. The laser emission below the threshold was also dominated by TE polarization and its degree of polarization was 0.48 that was larger compared with those of the previous reports of spontaneous emission of the AlGaN MQWs emitting near 250 nm grown on sapphire.<sup>14,27</sup> The TE dominance is caused by the topmost position of the heavy hole (HH) band of GaN and thereby the optical transition between the conduction band and the HH band.<sup>13</sup> The greater degree of polarization of the stimulated emission above the threshold than that of the spontaneous emission below the threshold can be attributed to the large TE-to-TM gain ratio amid the stimulated emission.<sup>28</sup>

In conclusion, we have demonstrated DUV lasing at 249 nm based on the AlN/GaN MQWs grown on the *c*-plane sapphire substrate by MOCVD. With good material and facet quality and large optical confinement factor, a low threshold of 190

kW/cm<sup>2</sup> was achieved that is comparable to state-of-the-art AlGaIn MQW lasers at similar wavelengths on AlN and sapphire substrates. The TE-dominant optical polarization was measured for the stimulated and spontaneous emissions above and below the threshold, respectively. These results demonstrate that the outstanding potentials of the AlN/GaN MQWs for DUV LEDs and lasers.

## AUTHOR INFORMATION

### Corresponding Authors

\*E-mail: cqchen@hust.edu.cn.

\*E-mail: daijiangnan@hust.edu.cn.

\*E-mail: xiaohang.li@kaust.edu.sa.

### ORCID

Wei Guo: 0000-0002-6233-0529

Jichun Ye: 0000-0002-3901-7155

Changqing Chen: 0000-0003-0899-708X

Jiangnan Dai: 0000-0001-9805-8726

Xiaohang Li: 0000-0002-4434-365X

### Author Contributions

<sup>†</sup>M.S. and Y.Z. contributed equally to this work.

### Notes

The authors declare no competing financial interest.

## ACKNOWLEDGMENTS

This work is supported by the National Key Research and Development Program of China (Grant No. 2016YFB0400901), the Key Laboratory of infrared imaging materials and detectors, Shanghai Institute of Technical Physics, Chinese Academy of Sciences (Grant No. IIMDKFJ-17-09), the National Natural Science Foundation of China (Grant Nos. 61704062, 61774065, and 61704176), the China Postdoctoral Science Foundation (Grant No. 2016M602287), and the Director Fund of WNLO. The KAUST authors appreciate the support of KAUST Baseline BAS/1/1664-01-01, GCC Research Council REP/1/3189-01-01, and Competitive Research Grants URF/1/3437-01-01 and URF/1/3771-01-01.

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