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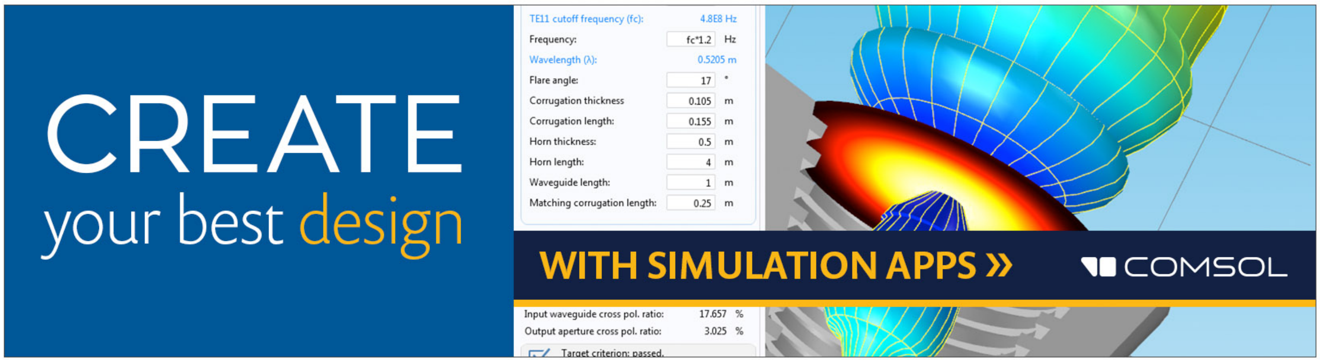

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Demonstration of transverse-magnetic deep-ultraviolet stimulated emission from AlGaN multiple-quantum-well lasers grown on a sapphire substrate

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We demonstrate transverse-magnetic (TM) dominant deep-ultraviolet (DUV) stimulated emission from photo-pumped AlGaN multiple-quantum-well lasers grown pseudomorphically on an AlN/sapphire template by means of photoluminescence at room temperature. The TM-dominant stimulated emission was observed at wavelengths of 239, 242, and 243 nm with low thresholds of 280, 250, and 290 kW/cm^2, respectively. In particular, the lasing wavelength of 239 nm is shorter compared to other reports for AlGaN lasers grown on foreign substrates including sapphire and SiC. The peak wavelength difference between the transverse-electric (TE)-polarized emission and TM-polarized emission was approximately zero for the lasers in this study, indicating the crossover of crystal-field split-off hole and heavy-hole valence bands. The rapid variation of polarization between TE- and TM-dominance versus the change in lasing wavelength from 243 to 249 nm can be attributed to a dramatic change in the TE-to-TM gain coefficient ratio for the sapphire-based DUV lasers in the vicinity of TE-TM switch. © *2015 AIP Publishing LLC*.
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The developments of III-nitride deep-ultraviolet (DUV) laser diodes (LDs) and light-emitting diodes (LEDs) have attracted considerable interest for a number of applications such as high-density optical storage and disinfection. Recently, low-threshold photo-pumped DUV lasers containing AlGaN multiple-quantum wells (MQWs) have been demonstrated by employing bulk AlN substrates.[1–7] The bulk AlN substrates were utilized because of their low dislocation density as well as reduction of lattice and thermal mismatch between the substrate and Al-rich AlGaN layers, resulting in a low dislocation density in the MQW active region and thus enhanced gain. However, because of the shortcomings of currently available AlN substrates, such as small area, strong DUV absorption, and high cost, it is more desirable to grow the DUV lasers on larger and lower-cost foreign substrates like sapphire that have been widely used to grow smaller-bandgap III-nitride materials. Recently, we have demonstrated photo-pumped AlGaN MQW DUV lasers grown on *c*-plane sapphire substrates with very low thresholds at 249 nm and 256 nm, indicating that sapphire can be a useful substrate for DUV LDs.[8]

One interesting property of AlGaN luminescence is the optical polarization determined by transitions between the conduction band and topmost valence band. When the topmost valence band is the heavy hole (HH) band, the dominant band transition is between the conduction band and HH band, which leads to transverse-electric (TE) ($E_{TE} \perp c$-axis) dominant emission. With an increased Al composition and thus a shorter emission wavelength, the split-off hole (CH) band moves closer to the conduction band relative to the HH band, which triggers the switch from TE- to transverse-magnetic (TM)-polarized ($E_{TM} \parallel c$-axis) emission when the CH band crosses over the HH band and thus becomes the topmost band.[9,10] The optical polarization can have a considerable impact on the performance of DUV LEDs and LDs. For top- or bottom-emitting LEDs grown on the *c*-plane substrates, TM-polarization can be detrimental for light extraction efficiency because the TM-polarized light is unlikely to emit from the surface that is parallel to the *c*-plane because of $E_{TM} \parallel c$-axis.[10] For edge-emitting LDs, TE polarization is also desirable as TE-polarized light does not penetrate as deeply into the smaller-bandgap *p*-type region as for TM-polarized light.

Previously, the above-threshold optical polarization of stimulated emission from photo-pumped AlGaN DUV lasers grown on AlN substrates emitting at 243–281 nm has been reported.[1–7] These studies show that TE-polarized stimulated emission was dominant in this wavelength range. For photo-pumped AlGaN DUV lasers grown on *c*-plane sapphire substrates, TE polarized emission dominated at $\lambda \geq 249$ nm.[8,11,12] Hence, there has been no observation of dominant TM-polarized stimulated emission for AlGaN DUV lasers grown on AlN or sapphire substrates to date. There was one report for the optical polarization of stimulated emission from a photo-pumped AlGaN DUV laser grown on a *c*-plane SiC substrate, showing TM-dominance at 240.8 nm.[10] However, no TE-dominant lasing has been reported for III-nitride structures on SiC substrates. Therefore, there is a lack of experimental observation of TE-TM switching of stimulated emission from lasers grown on any substrate and thus the

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valence band crossover for AlGaN DUV lasers, which is important for design of a laser structure with TM-dominant stimulated emission at shorter wavelengths.

In this study, TM-dominant DUV stimulated emission from AlGaN MQW lasers grown on sapphire was demonstrated due to lasing at short wavelengths of 239–243 nm. Optical polarization was analyzed and compared with previous reports. X-ray diffraction (XRD), transmission electron microscopy (TEM), and room temperature (RT) power-dependent photoluminescence (PL) experiments were conducted to characterize the material structure and emission.

As shown schematically in Figure 1(a), the AlGaN DUV laser structure was grown on a 2-in. diameter *c*-plane AlN/sapphire template in an AIXTRON 3 × 2″ close-coupled showerhead metalorganic chemical vapor deposition (MOCVD) reactor. The AlN/sapphire template similar to this used in our previous studies for the growth of low-threshold DUV AlGaN lasers emitting at 249 and 256 nm at RT[8,13,14] was utilized in this work. A graded AlGaN waveguide (WG) layer was grown on the AlN template, followed by five periods of 1.0-nm-$Al_{0.66}Ga_{0.34}N$/4.1-nm-$Al_{0.83}Ga_{0.17}N$ MQWs. The thicknesses of quantum well and barrier were determined by high-resolution cross-sectional TEM experiment, as shown in Figure 2. AlGaN instead of AlN was used for the quantum barrier (QB) as the larger bandgap of AlN QB layers can impede carrier transport in an electrically driven device and the AlGaN QB layers can contribute to better optical confinement in the MQWs because of higher refractive index than that of AlN. The growth was concluded with a thin AlGaN cap layer for surface passivation. As shown in Figure 1(b), the asymmetric (105) reciprocal space map (RSM) measurements by XRD indicated the AlGaN layers were pseudomorphically grown on the AlN template layer. Thus, the structure retained a similar quality and in-plane lattice constant as that of the AlN template layer.

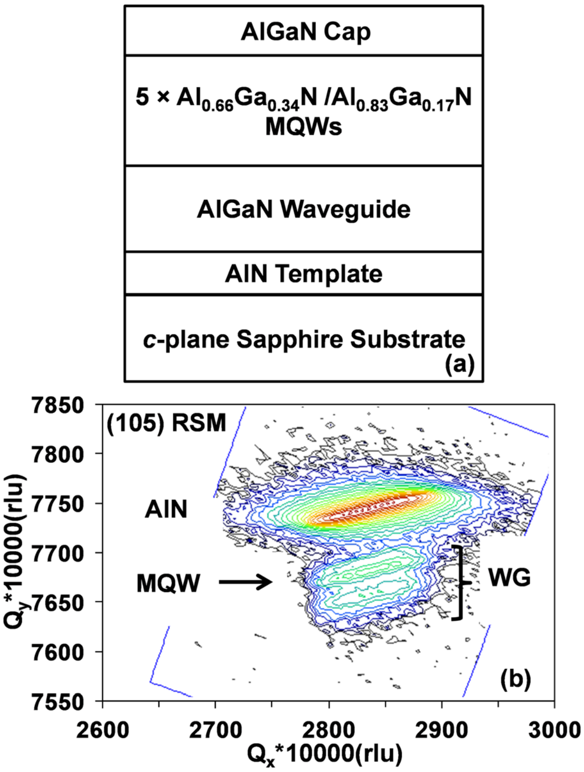

FIG. 1. (a) The cross-sectional schematic diagram and (b) XRD (105) RSM of the AlGaN MQW laser structure grown on a *c*-plane AlN/sapphire template.

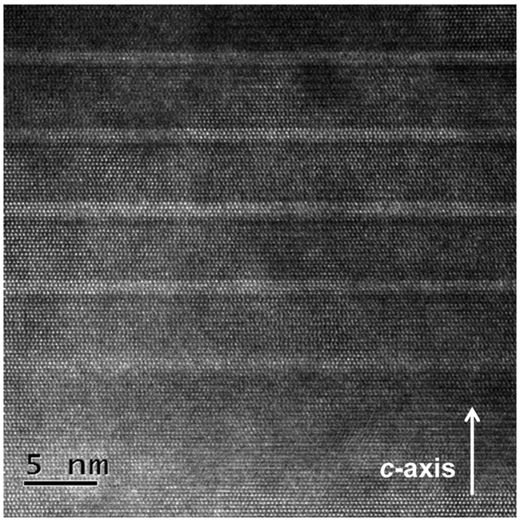

FIG. 2. A cross-sectional TEM image of the MQW active region.

Subsequently, the wafer was cleaved into Fabry-Perot laser bars by mechanical scribing from back side of the wafer. No DUV high-reflection coatings were deposited onto the cavity facets. A pulsed ArF excimer laser ($\lambda = 193$ nm) was used to excite the laser bars at RT. The excitation laser beam with a controlled degree of attenuation passed through a rectangular aperture with a defined area, and then excited the epitaxial surface of the laser bars uniformly. The in-plane light emission was collected from the laser cavity facet by an optical fiber placed near the facet. The measurements of optical polarization were performed by employing an alpha-BaB_2O_4 (BBO) polarizer. More details of the experimental setup can be found elsewhere.[3]

Figures 3(a)–3(c) show PL spectra of the lasers emitting at 239, 242, and 243 nm under different excitation power densities, respectively. Cavity lengths of the 239-nm, 242-nm, and 243-nm lasers are 1.1, 2.2, and 1.8 mm, respectively. The small wavelength variation of ∼4 nm in the emission wavelengths of these lasers are due to lateral wafer inhomogeneities, which can include variation of strain state, composition, layer thickness, and carrier density.[15–19] As the excitation power density increased, the spectral linewidth narrowed significantly and reached FWHM values of 1.4–2.3 nm at respective maximum excitation power density, which indicated stimulated emission.[2,3] The laser thresholds were estimated to be 280, 250, and 290 kW/cm^2 for the 239-nm, 242-nm, and 243-nm lasers, respectively. These thresholds are lower than those of the reported lasers at similar wavelengths grown on bulk AlN substrates.[1,3] Some possible reasons for lower thresholds were discussed previously, which include impurity absorption within AlN substrate and different designs of laser structures.[8] The stimulated emission peak at 239 nm is the shortest RT lasing wavelength yet reported for AlGaN DUV lasers grown on foreign substrates including sapphire and SiC.[8,11,12] In addition, we have not observed a clear trend, where the thresholds are strongly correlated to the cavity length. The small variation of thresholds can be affected by the on-wafer variations of dislocation

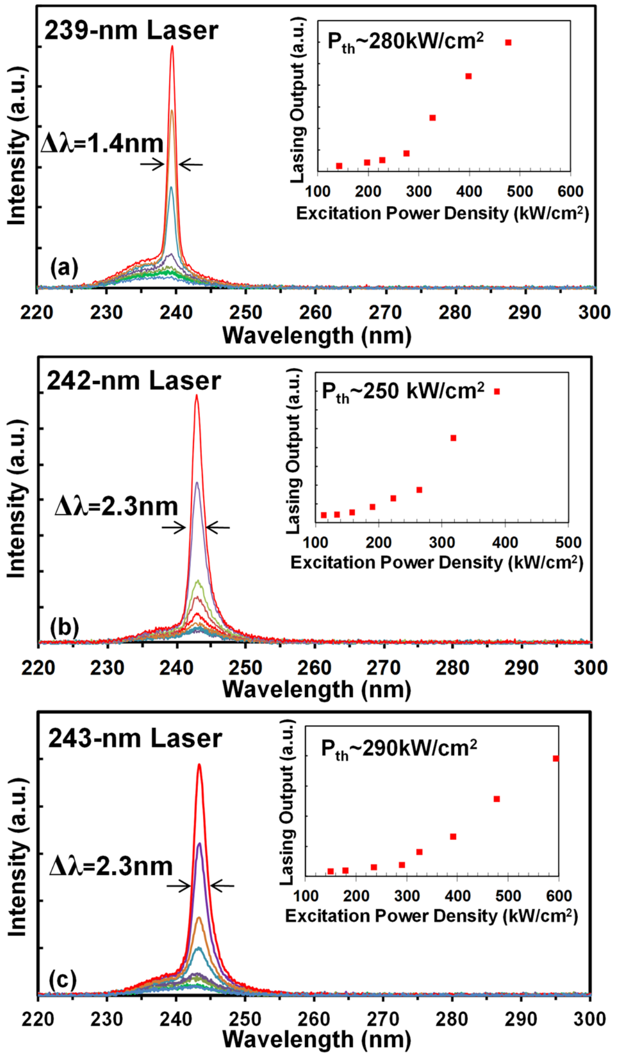

FIG. 3. Emission spectra of the (a) 239-nm, (b) 242-nm, and (c) 243-nm lasers by power-dependent PL at RT. The insets show the respective light output intensity of stimulated emission as a function of excitation power density.

density, thickness, composition, and strain as well as facet condition.

Figures 4(a)–4(c) show spectra of TE- and TM-polarized laser emission from the 239-nm, 242-nm, and 243-nm lasers operating at about three times as high as their respective threshold (P_{th}). Spectra of the 239-nm, 242-nm, and 243-nm lasers were dominated by TM-polarized stimulated emission accompanied by weak TE-polarized spontaneous emission. This observation of TM-dominant stimulated emission from DUV lasers grown on sapphire substrates is attributed to the short lasing wavelengths of these samples in this study. The polarization degree, defined as $\rho = (I_{TE} - I_{TM})/(I_{TE} + I_{TM})$, was calculated wherein I_{TE} and I_{TM} represent the integrated spectral intensity of TE- and TM-polarized emission, respectively. The ρ values were −0.40, −0.65, and −0.67 for the 239-nm, 242-nm, and 243-nm lasers, respectively. These results suggest that the dominant interband transition took place between the conduction band and CH valence band for lasing wavelengths equal to or shorter than 243 nm.

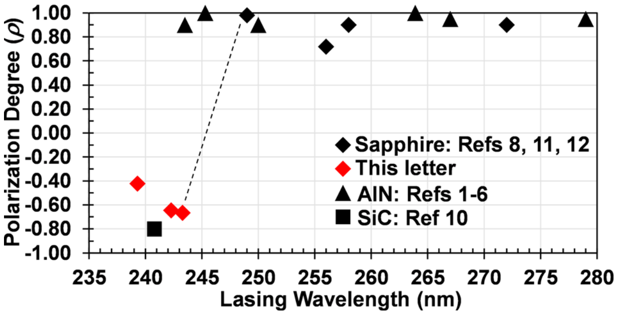

FIG. 5. Summary of the reported above-threshold polarization degree (ρ) of DUV lasers grown on AlN, sapphire, and SiC substrates.

Previously, the peak wavelength difference of TE- and TM-polarized emission above threshold was measured to be 1.6 nm ($\lambda_{TE} > \lambda_{TM}$) for the AlGaN MQW laser grown on a bulk AlN substrate which exhibited TE-dominant lasing at 243.5 nm, suggesting an energy separation of ∼34 meV between the HH and CH bands.[3] However, as shown in Figures 4(a)–4(c), the peak wavelength difference of the TE- and TM-polarized emission above threshold was negligible for all the lasers grown on sapphire. This indicates that the energy separation between the HH and CH bands was minimal. In other words, the HH band and CH band crossed over for the laser structure employed in this work.

Figure 5 summarizes the reported above-threshold polarization degree, ρ, of DUV lasers grown on AlN,[1–6] sapphire,[8,11,12] and SiC[10] substrates. The polarization of laser grown on the SiC substrate was TM-dominant at 240.8 nm. The polarization of lasers grown on AlN substrates was

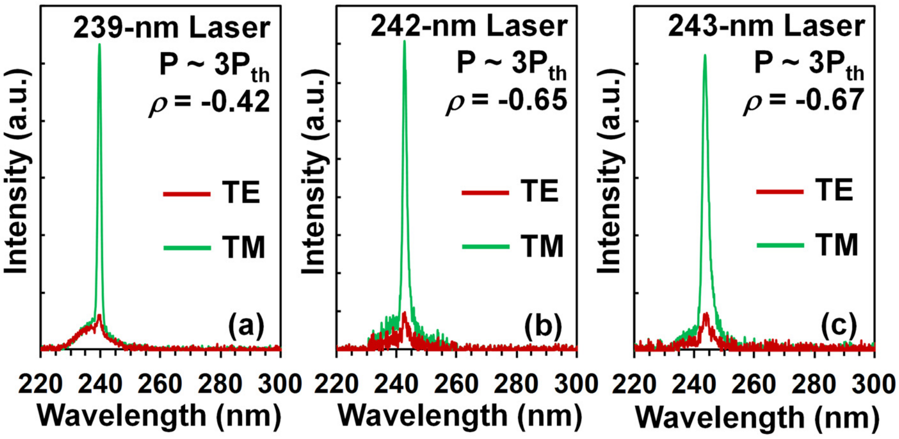

FIG. 4. TE- and TM-polarized spectra of the (a) 239-nm, (b) 242-nm, and (c) 243-nm lasers above respective threshold, showing TM-dominant stimulated emission.

TE-dominant at $\lambda \geq 243.5\,\text{nm}$. For the lasers grown on sapphire substrates, the polarization was TE-dominant at $\lambda \geq 249\,\text{nm}$. Based on this study, the TM-polarized emission dominated the lasing spectra at $\lambda \leq 243\,\text{nm}$ for the lasers grown on sapphire substrates. Thus, both TE- and TM-dominant DUV stimulated emission from lasers grown on sapphire have been demonstrated. As indicated by the dashed line in Figure 5, the rapid variation between TE- and TM-dominance with respect to the change in lasing wavelength from 243 to 249 nm is distinct from the previous studies, wherein the spontaneous emission from AlGaN structures made a similar extent of polarization switch at a considerably longer wavelength span.[9,20,21] This can be attributed to the dramatic change in the ratio of TE-to-TM gain coefficients for the DUV AlGaN MQW lasers in the vicinity of TE-TM switch.[17]

In summary, TM-dominant DUV stimulated emission from photo-pumped AlGaN MQW lasers grown by MOCVD on sapphire substrates were demonstrated at RT. TM-dominant stimulated emission was observed at 239, 242, and 243 nm with low thresholds of less than 300 kW/cm^2. There was no peak wavelength difference of the TE- and TM-polarized emission, indicating crossover of the CH and HH bands in the AlGaN MQWs. The rapid change of polarization between TE- and TM-dominance versus the change in lasing wavelength from 243 to 249 nm suggests a large variation of the ratio of TE-to-TM gain coefficients for the DUV AlGaN MQW lasers near TE-TM switch. Hence, this work also provides insights for the design of DUV lasers operating near the TE-TM switch.

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