The optical gain characteristics of high Al-content AlGaN quantum wells (QWs) are analyzed for deep UV lasers. The effect of crystal-field split-off hole (CH) and heavy-hole (HH) bands crossover on the gain characteristics of AlGaN QW with AlN barriers is analyzed. Attributing to the strong transition between conduction–CH bands, the TM spontaneous emission recombination rate is enhanced significantly for high Al-content AlGaN QWs. Large TM-polarized material gain is shown as achievable for high Al-content AlGaN QWs, which indicates the feasibility of TM lasing for lasers emitting at ~220–230 nm. © 2010 American Institute of Physics. [doi:10.1063/1.3488825]
significantly enhanced attributing to the strong transition between conduction band and CH band. The reduction in the TE-polarized $R_{sp}$ for high Al-content AlGaN QW can be attributed to the significantly lower carrier density populating the HH and LH bands from the increasing energy separation between CH and HH/LH bands.

Figure 2(b) shows both the TE ($g_{peak}^{TE}$) and TM peak material gains ($g_{peak}^{TM}$) as a function of Al-content for the 3 nm Al$_{0.6}$Ga$_{0.4}$N QW with AlN barriers calculated for $n=5 \times 10^{19}$ cm$^{-3}$ at $T=300$ K. For Al$_{0.6}$Ga$_{0.4}$N QW with $x<68\%$, both the $g_{peak}^{TE}$ and $g_{peak}^{TM}$ are relatively low ($g_{peak} < 500$ cm$^{-1}$), however the $g_{peak}^{TM}$ is relatively larger than the $g_{peak}^{TE}$. For Al$_{0.6}$Ga$_{0.4}$N QW with $x>68\%$, the $g_{peak}^{TM}$ is dominant resulting in significantly higher peak gain ($g_{peak}^{TM} = 3280$ cm$^{-1}$ for $x=70\%$, and $g_{peak}^{TM} = 4690$ cm$^{-1}$ for $x=80\%$).

The gain analysis indicates that the carriers in the high Al-content AlGaN QW are dominantly confined in the CH band after the crossover of the HH/LH and CH bands, resulting in higher than one-order of magnitude ratio of $g_{peak}^{TM} / g_{peak}^{TE}$.

Figure 3(a) illustrates the spontaneous emission recombination rate per unit volume ($R_{sp}$) for 3 nm thick Al$_{0.6}$Ga$_{0.4}$N QW sandwiched by AlN barrier layers with carrier density ($n$) up to $n=6 \times 10^{19}$ cm$^{-3}$. The analysis was carried out for AlGaN QW with $x=60\%–80\%$. For the Al$_{0.6}$Ga$_{0.4}$N QW (or Al$_{0.7}$Ga$_{0.3}$N QW), the increase in the spontaneous emission rate ($R_{sp}$) as a function of carrier density ranges between 3.4–3.9 times (or 5.4–10.5 times) higher compared to that of the Al$_{0.6}$Ga$_{0.4}$N QW. The enhancements of the $R_{sp}$ for high Al-content ($x=70\%$, 80\% AlGaN QWs are attributed to the increase in the TM-polarized spontaneous emission rate for AlGaN QW with Al-content above ~68\%.

Figure 3(b) shows the TE- and TM-polarized optical gain spectra for Al$_{0.6}$Ga$_{0.4}$N QWs with $x=60\%–80\%$. The peak gain wavelengths ($\lambda_{peak}$) for Al$_{0.6}$Ga$_{0.4}$N QW with $x=60\%$, 70\%, and 80\% are 247.5 nm, 231.3 nm, and 221.8 nm, respectively. For Al$_{0.7}$Ga$_{0.3}$N QW, both the TE- and TM-polarized gains are relatively low (~400–500 cm$^{-1}$). However, for the case of higher Al-contents ($x=70\%$, $x=80\%$), the TM-polarized gains increase dramatically, while the TE-polarized gains are significantly lower.

Figures 4(a) and 4(b) show the TM- and TE-polarized material gains ($g_{peak}^{TM}$ and $g_{peak}^{TE}$) for high Al-content AlGaN QW as a function of carrier density, respectively. The $g_{peak}^{TM}$ for the Al$_{0.8}$Ga$_{0.2}$N QW and Al$_{0.7}$Ga$_{0.3}$N QW are found to be significantly larger. For Al$_{0.7}$Ga$_{0.3}$N QW, the $g_{peak}^{TM}$ is 1.5–4.3 times larger than that of the $g_{peak}^{TE}$. For Al$_{0.8}$Ga$_{0.2}$N QW, the $g_{peak}^{TM}$ is ~20–110 times that of the $g_{peak}^{TE}$, attributing to its significantly larger energy separation of the CH and HH/LH bands. At $n=5 \times 10^{19}$ cm$^{-3}$, the $g_{peak}^{TM}$ of Al$_{0.8}$Ga$_{0.2}$N QW and Al$_{0.7}$Ga$_{0.3}$N QW are 4690 cm$^{-1}$ and 3280 cm$^{-1}$, respectively. The $g_{peak}^{TE}$ of Al$_{0.8}$Ga$_{0.2}$N QW and Al$_{0.7}$Ga$_{0.3}$N QW were found as 230 cm$^{-1}$ and 765 cm$^{-1}$ (at $n=5 \times 10^{19}$ cm$^{-3}$), which are relatively negligible compared to the $g_{peak}^{TM}$. In contrast to the higher Al-content AlGaN QWs, the $g_{peak}^{TM}$ and $g_{peak}^{TE}$ are relatively similar for the Al$_{0.6}$Ga$_{0.4}$N QW. The $g_{peak}^{TM}$ and $g_{peak}^{TE}$ of the Al$_{0.6}$Ga$_{0.4}$N QW at $n=7 \times 10^{19}$ cm$^{-3}$ are 1425 cm$^{-1}$ and 1610 cm$^{-1}$, respectively. Thus, the TM-polarized lasing is feasible for high Al-content AlGaN QW lasers in the 220–230 nm spectral range.

To analyze the threshold properties of deep UV lasers, AlGaN QW lasers with optical confinement factor ($\Gamma_{opt}$) of 0.02 (Ref. 33) were employed in the analysis. The internal losses ($\alpha_i$) in typical AlGaN lasers range from 14 cm$^{-1}$ (Ref.
The effect of CH and HH bands crossover on the gain for large TM-polarized material gain is achievable for high Al- (1019 cm−3) and 3.9×1019 cm−3 are obtained for Al0.3Ga0.7N QW and Al0.7Ga0.3N QW, respectively. For the lasers with gth ~3050 cm−1, the threshold carrier densities (nth) are 3.5×1019 cm−3 and 4.9×1019 cm−3 are obtained for Al0.3Ga0.7N QW and Al0.7Ga0.3N QW, respectively.

In summary, the gain characteristics of the high Al-content AlGaN QWs are analyzed for deep UV lasers. The effect of CH and HH bands crossover on the gain for the AlGaN QWs for lasers is clarified. After the crossover of the HH/LH and CH bands, the band-edge energy level of CH band is larger than those of the HH/LH bands. The TM-polarized Rth and material gain are dominant for AlGaN QW with x > 68%. The spontaneous emission rate is significantly enhanced for high Al-content Al1−xGaxN QW (x = 70%, 80%) attributing to the strong transition between conduction band and CH band. The gain analysis shows that large TM-polarized material gain as achievable for high Al-content Al1−xGaxN QWs, which indicates the feasibility of TM lasing for deep UV lasers emitting at ~220–230 nm.

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