Large optical gain AlGaN-delta-GaN quantum wells laser active regions in mid- and deep-ultraviolet spectral regimes

Jing Zhang, Hongping Zhao, and Nelson Tansu
Department of Electrical and Computer Engineering, Center for Optical Technologies, Lehigh University, Bethlehem, Pennsylvania 18015, USA

(Received 18 February 2011; accepted 7 April 2011; published online 28 April 2011)

The gain characteristics of high Al-content AlGaN-delta-GaN quantum wells (QWs) are investigated for mid- and deep-ultraviolet (UV) lasers. The insertion of an ultrathin GaN layer in high Al-content AlGaN QWs leads to valence subbands rearrangement, which in turn results in large optical gain for mid- and deep-UV lasers. © 2011 American Institute of Physics. [doi:10.1063/1.3583442]

Nitride semiconductors have important applications for lasers and light-emitting diodes (LEDs), power electronics, thermoelectricity, solar cells, and terahertz photonics. The electrically-injected AlGaN quantum wells (QWs) lasers have been realized in the emission wavelength (λ) ~ 320–360 nm. Up to today, no electrically injected mid-(λ ~ 250–320 nm) and deep-ultraviolet (UV) (λ ~ 220–250 nm) lasers have been realized. Recent theoretical works have been reported on the gain properties for both low and high Al-content AlGaN QWs while the detailed studies on gain properties of high Al-content AlGaN QWs are still lacking.

Our recent work revealed that the use of high Al-content AlGaN QWs resulted in strong conduction (C)-valence subbands rearrangement, which in turn results in large TE-gain deep-UV QW and large TM-gain mid-UV QW. Meanwhile, the Al-content content AlGaN QWs are still lacking.

In this letter, we present the gain properties of high Al-content (x) AlGaN quantum wells (QWs) with large transverse-electric (TE) polarized gain at λ ~ 220–300 nm. The delta-QW is realized by the insertion of GaN delta-layer (3–9 Å) in high Al-content AlGaN QW leading to strong valence subbands rearrangement. The band structures and wave functions were calculated based on 6-band k-p formalism taking into account the valence band mixing, strain, polarization fields, and carrier screening effects with the band parameters obtained from Refs. 44–46.

Figure 1 shows the material gains calculated for 3 nm conventional AlGaN (x) QW with AlN barriers with x = 20%. Large TM-polarized material gains (gTM) are achievable for AlGaN with x = 70% and 80% (λpeak ~ 220–230 nm), which is two times greater than that of the corresponding TE gains. In addition, the conventional AlGaN QWs in the 250–320 nm spectral range are limited to relatively low TE and TM gains for Al-contents below 60% (Fig. 1).

The low gain for the AlGaN QW in the 250–320 nm spectral regime is attributed to the significant band filling for the heavy-hole (HH)/light-hole (LH) and CH subbands. Thus, the pursuit of mid-UV AlGaN-based QW with large gain is of great importance for lasers. The availability of large TE-gain mid-UV QW is also important for laser structures that require high TE gain.

By employing the AlGaN-delta-GaN QW, the strong valence band mixing results in the valence subband rearrangement, which in turn leads to (1) higher HH1 and LH1 subband energy levels in comparison to that of the CH1 subband, (2) splitting of the HH1 and LH1 subbands, and (3) dominant C1-HH1 transition leading to large TE gain. Thus, large TE gains in the deep- and mid-UV spectral regimes are achievable with the AlGaN-delta-GaN QW.

Figures 2(a) and 2(b) show the valence band structures for both conventional 30 Å Al0.8Ga0.2N QW and 30 Å Al0.8Ga0.2N, the CH1 subband energy is much larger than those of the HH and LH subbands [Fig. 2(a)]. In contrast, the HH1 and LH1 subbands are rearranged into higher subband energy levels than those of the CH1 subband for the 30 Å Al0.8Ga0.2N QW (delta-QW). The energy separation between the HH1 and CH1 subbands for the Al0.8Ga0.2N QW is relatively large (~ 140 meV) at T = 300 K, which results in dominant C1-HH1 transition.

Figure 3(a) shows both the TE and TM optical gain spectra for 30 Å Al0.8Ga0.2N QW with n = 5 × 1019 cm−3 at T = 300 K. Attribution to the insertion of the AlGaN delta-layer into AlGaN QW, the band energies of HH and LH subbands are increased significantly than that of the AlGaN QW.

FIG. 1. (Color online) TE and TM material gains as a function of Al-content (x) for 3 nm AlGaN QW with AlN barriers for n = 5 × 1019 cm−3 and 6 × 1019 cm−3, with the emission wavelengths (λ) at n = 5 × 1019 cm−3.
of the CH subband. Thus, the TE gains for both 30 Å Al_{0.7}Ga_{0.3}N QW and 30 Å Al_{0.8}Ga_{0.2}N/3 Å GaN QW become dominant. The use of AlN barriers.

Thus, the use of AlGaN-delta-GaN QW leads to high gain material for \( \lambda_{\text{peak}} \approx 240–300 \) nm, as well as large TE gain in the deep UV spectral regime.

Figure 4(b) shows the TE material gain as a function of carrier density at \( T=300 \) K for 30 Å Al_{0.7}Ga_{0.3}N/3 Å GaN QW, 30 Å Al_{0.8}Ga_{0.2}N/3 Å GaN QW (x=0.7, 0.8), and conventional 30 Å Al_{x}Ga_{1-x}N QW (x=0.7, 0.8). The 30 Å Al_{0.7}Ga_{0.3}N/9 Å GaN QW shows transparency carrier density (\( n_{tr} \)) of \( n_{tr} \approx 1.0 \times 10^{19} \) cm\(^{-3} \), and the \( n_{tr} \approx 1.8 \times 10^{19} \) cm\(^{-3} \) are obtained for both 30 Å Al_{0.8}Ga_{0.2}N/3 Å GaN QW and 30 Å Al_{0.8}Ga_{0.2}N/3 Å GaN QW. All the delta QW gain media exhibit significantly higher TE material gains, in comparison to those of conventional AlGaN QWs [Fig. 4(b)]. For \( n > 4 \times 10^{19} \) cm\(^{-3} \), the TE material gain for Al_{0.7}Ga_{0.3}N/3 Å GaN QW is \( \approx 105–126 \) times of the Al_{0.8}Ga_{0.2}N/3 Å GaN QW, which is attributed from better carrier confinement that leads to larger momentum matrix element. In comparison to the conventional 30 Å Al_{x}Ga_{1-x}N QW, the insertion of 3 Å GaN delta-layer in the 30 Å Al_{x}Ga_{1-x}N QW active regions lead to increase in TE gain up to \( \approx 5.8 \) times and \( \approx 6.0 \) times while the increase in TE gain is \( \approx 5.3 \) times for 30 Å Al_{0.8}Ga_{0.2}N/3 Å GaN QW in comparison to that of conventional 30 Å Al_{0.7}Ga_{0.3}N QW.

The threshold properties of AlGaN-delta-GaN QW were analyzed. The laser structure (\( L_{\text{cav}}=500 \) μm) with optical confinement factor of 0.02 (Ref. 37) and mirror loss of 11 cm\(^{-1} \) was used, and the internal loss was 50 cm\(^{-1} \).

The threshold gain (\( g_{\text{th}} \)) was \( \approx 3050 \) cm\(^{-1} \). From Fig. 4(b), the threshold carrier densities (\( n_{th} \)) are 4.4 \times 10^{19} \) cm\(^{-3} \) and 4.2
and Al\textsubscript{0.7}Ga\textsubscript{0.3}N mid- and deep-UV lasers. Al-content AlGaN delta-GaN QWs as active regions for 

In summary, the gain characteristics of high Al-content AlGaInGaN QWs are analyzed for mid- and deep-UV lasers. 

The work is supported by U.S. National Science Foundation (Grant Nos. ECCS 0701421 and ECCS 1028490) and Class of 1961 Professorship Fund.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure.png}
\caption{(Color online) (a) TE optical gain for 30 Å Al\textsubscript{0.8}Ga\textsubscript{0.2}N/3 Å GaN QW at n=5×10\textsuperscript{19} cm\textsuperscript{-3} and (b) TE material gain as a function of carrier density for 30 Å Al\textsubscript{0.8}Ga\textsubscript{0.2}N/9 Å GaN QW, 30 Å Al\textsubscript{0.7}Ga\textsubscript{0.3}N/3 Å GaN QW (x=0.7, 0.8), and 30 Å Al\textsubscript{0.7}Ga\textsubscript{0.3}N/9 Å GaN QW (x=0.7, 0.8).}
\end{figure}

×10\textsuperscript{19} cm\textsuperscript{-3} for Al\textsubscript{0.8}Ga\textsubscript{0.2}N/3 Å GaN QW (λ≈245 nm) and Al\textsubscript{0.7}Ga\textsubscript{0.3}N/3 Å GaN QW (λ≈254 nm), respectively. For mid UV lasers (λ≈293 nm) using Al\textsubscript{0.7}Ga\textsubscript{0.3}N/9 Å GaN QW, the n\textsubscript{th} is 3.3×10\textsuperscript{19} cm\textsuperscript{-3}.

In summary, the gain characteristics of high Al-content AlGaInGaN delta-GaN QWs are analyzed for mid- and deep-UV lasers. 

The work is supported by U.S. National Science Foundation (Grant Nos. ECCS 0701421 and ECCS 1028490) and Class of 1961 Professorship Fund.