Injection Inhomogeneity and Lasing Thershold in III-Nitride Multi-QW Deep-UV Laser Diodes

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Abstract—**Lasing threshold conditions have been analyzed in deep-UV (DUV) multiple-QW (MQW) III-nitride laser diode (LD) structures with different QW confinement depth. Shallow QWs with smaller internal polarization fields reveal better QW emission characteristics including lower QW transparency population and higher differential gain. In MQW LD structures, however, the high-gain operation of shallow QWs is hindered by insufficient QW injection due to increased carrier leakage from shallow-QW active region. Deep active QWs can attain higher operational populations and provide for higher LD optical gain; however, LDs designed with deeper active QWs suffer from MQW population non-uniformity due to increased inhomogeneity of carrier injection. Underpumped deep QWs reduce the total modal gain of the LD structure thus deteriorating the lasing threshold and LD power conversion (wall-plug) efficiency.**

Keywords—***UV emission; multiple quantum wells; laser diodes; lasing threshold; inhomogeneous carrier injection.***

I. Introduction

Lasing action at wavelength below 300 nm remains a highly challenging problem for III-nitride based laser diodes. Inferior hole injection in wide-band-gap AlGaN semiconductors accentuates the necessity of optimal LD active region design which usually includes several active QWs [1]. Multi-QW active regions of III-nitride based emitters suffer from inhomogeneous carrier distribution, uneven QW injection conditions, and imbalanced populations of optically active QWs which critically limit the device performance [2]. Active QW depth plays a crucial part in establishing the MQW injection conditions [3]. In this work, we study the effect of QW depth on injection uniformity and lasing threshold in MQW DUV LDs. To simplify the analysis, all structures are designed with the same 4-QW layout of the active region. For device modeling, we use COMSOL-based in-house simulation package developed at Ostendo Technologies Inc. [4].

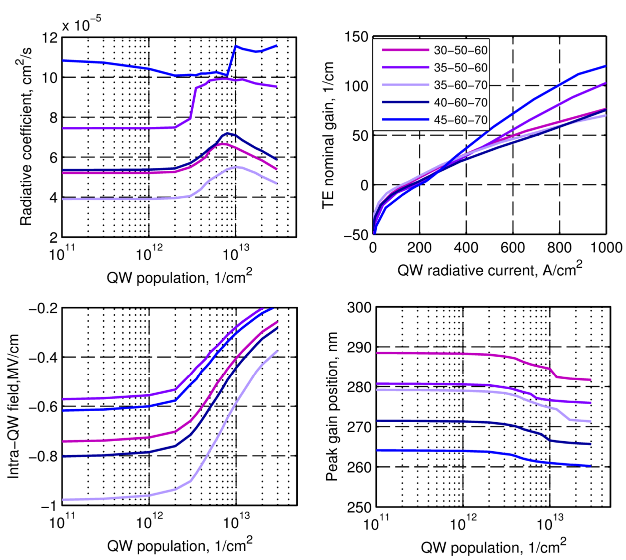

Fig. 1. Calculated characteristics of DUV-emitting QWs with different confinement depth. The legend indicates aluminum percent contents in QW, waveguide (barrier), and cladding layers.

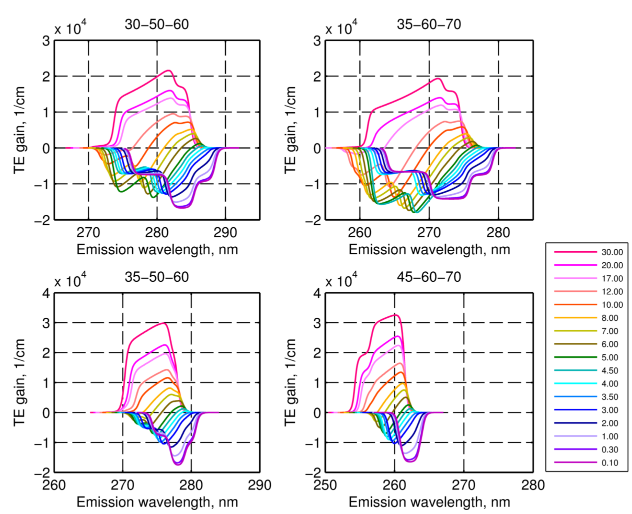

Fig. 2. TE gain spectra of selected QWs with shallow (upper subplots) and deep (lower subplots) confinement depth. The legend indicates QW carrier concentration in $10^{12}/cm^2$. QWs are labeled as in Fig. 1

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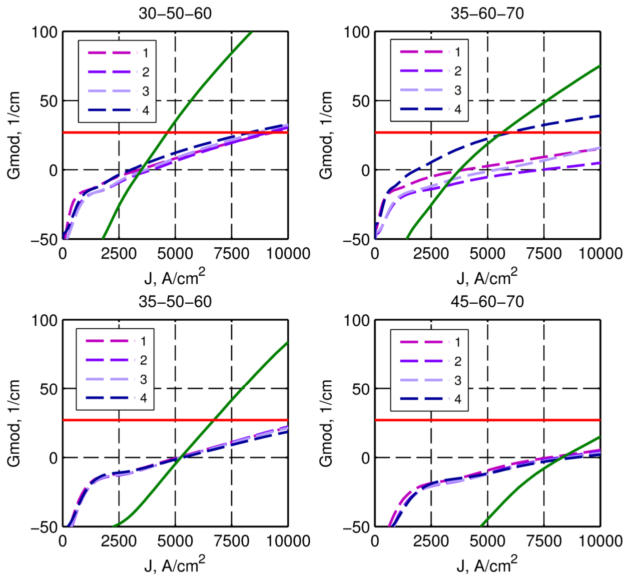

Fig. 3. Threshold condition in 4-QW DUV LD structures. Red line - total optical loss; green line - total modal gain. Dashed lines show partial modal gains of specific QWs counted from N-side of the diode. Shallow-QW LD structures (lower subplots) demonstrate more uniform MQW injection but suffer from insufficient QW populations and lower gain.

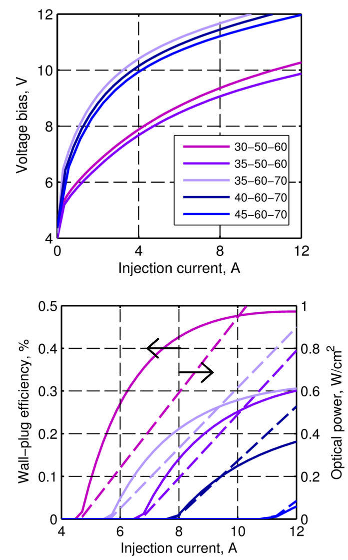

Fig. 4. Output characteristics of 4-QW LD structures specified by the legend in the upper subplot. LD performance degrades with decreasing active QW depth and/or increasing overall aluminum composition; combination of both trends being detrimental for structure 45-60-70 (structure codes: QW-Waveguide-Cladding aluminum in percent).

II. Simulation Results

Figure 1 presents the cumulative results of active QW simulation. QW structure codes indicate QW, barrier (waveguide), and cladding aluminum compositions in percent. QW radiative characteristics apparently correlate with intra-QW built-in polarization field. Shallow QWs with lowest intra-QW polarization field demonstrate the highest radiative and modal gain coefficients and the lowest blue shift of peak emission.

Figure 2 shows TE optical gain spectra of QW structures with different aluminum compositions. Legend indicates QW injection level in terms of confined carrier population (in 10^{12} cm^{-2}). Shallower QWs demonstrate narrower gain spectra and higher differential peak gain.

Figure 3 presents the threshold condition analyses in 4-QW LD structures with active QWs of different confinement depth. Red line indicates the level of total optical loss; green line shows calculated modal gain. Dashed lines present partial modal gains of specific QWs counted from N-side of the diode. Shallow-QW structures (lower subplots) demonstrate more uniform MQW injection but apparently suffer from insufficient QW populations and lower QW gain.

Figure 4 allows comparison of I-V characteristics and output performance (efficiency and optical power) of simulated LD structures. The output performance degrades with decreasing active QW depth and/or increasing overall waveguide-cladding aluminum composition; combination of both trends being crucial for structure 45-60-70 which is characterized by the highest overall aluminum composition.

III. Conclusions

Simulation of MQW DUV LD structures shows that active region injection efficiency degrades in designs which employ shallow active QWs, while employing deeper QWs aggravates the non-uniformity of MQW population. Both trends degrade the structure modal gain thus deteriorating the laser threshold.

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