Quantum well-width dependence study on AlGaN based UVC laser

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***Abstract*— A study of the well-width impact on the AlGaN laser is presented. The laser threshold and optical gain are significantly influenced by the quantum well design. A low threshold of 5 kw/cm^2 is achieved in the 3 nm well width due to a reduced QCSE.**

Keywords—UV laser design, QCSE, Well width, Gain spectrum, Laser threshold.

I. Introduction

Pursuing AlGaN-based optoelectronic devices require state-of-the-art control of dislocations and point defects to achieve the expected performance. Recently, it was demonstrated that AlGaN multiple quantum well (MQW) lasers grown on low-dislocation-density bulk AlN substrates can achieve high internal quantum efficiencies (IQE=95 %), low laser threshold (I_{Th}=6 kW/cm^2), as well as tunable lasing wavelength from 200 nm to 300 nm. This was achieved by reducing non-radiative recombination centers using point defect control strategies, such as chemical potential control and defect quasi Fermi level control. [1]-[7] Although a significant progress has been made for the optically-pumped laser structure, no electrically injected lasing has been demonstrated below 320 nm yet. It is suspected that the main challenge in the realization of mid-UV laser diodes is related to Mg doping and hole injection. [8]-[10] Mg-doped Al-rich AlGaN exhibits a high activation energy (~ 400 meV), which is not favorable for the hole injection layer. To enhance the carrier injection into the device, a thin p-GaN contact layer is typically used as a hole injection layer. Although it will lead to a partial absorption of the UV laser light, Mg-doped GaN layer leads to low contact resistance and efficient carrier injection. However, using p-GaN as a hole injection layer will also cause an interfacial barrier between p-GaN and 75 % Al-content AlGaN cladding layer. The barrier height is around 0.5 eV, which is detrimental for the hole injection. To overcome this barrier, a graded AlGaN is typically inserted between these two layers. Additionally, high resistivity Mg-doped Al-rich AlGaN waveguide & cladding layer is another factor limits the electrical performance of mid-UV laser. Although a high free hole concentration has been recently reported, the poor hole mobility leads to a poor conductivity in p-AlGaN. [11] To mitigate these impacts on the p-side, we previously proposed an optimized mid-UV laser structure design and predicted a turn-on current density of 5 kA/cm^2. [5]

Apart from doping and carrier injection, MQW design is of utmost importance as it will influence the overlap between electron and hole wave functions, carrier and optical confinement, gain spectrum, and ultimately the laser threshold. Unlike GaAs or InP infrared LDs, the performance of III-nitride laser is greatly dependent on MQW design because of the strong quantum confined Stark effect (QCSE). The origin of the QCSE has been discussed over years and has been attributed to a strong polarization field (spontaneous (SP) and piezoelectric (PZ) polarization) in the III-nitride materials. This effect will cause a spatial separation between electron and hole wavefunctions and decrease the radiative recombination rate. Although a thin quantum well design can increase carrier localization and mitigate the Stark effect [1], Kuramta et al. and Chow et al. found the QCSE still plays a very important role on the threshold current density in InGaN laser. [12], [13] So far, extensive studies have been conducted in InGaN lasers, but only little research has been done for Al-rich AlGaN laser.

In this work, we present a comprehensive study of the influence of the quantum well width on the optical properties of Al-rich AlGaN laser. We find the laser threshold power density and optical gain are significantly influenced by the MQW design due to the QCSE. A low laser threshold of 5 kw/cm^2 and a high peak gain of 80 cm^{-1} are achieved in the 3 nm well width AlGaN MQW.

II. Experimental

Low-pressure metalorganic chemical vapor deposition (LP-MOCVD) was used to grown AlGaN MQW structures on c-plane AlN single crystal substrates. Trimethylaluminum (TMA), triethylgallium (TEG), and ammonia (NH_3) were used as sources for Al, Ga, and N, respectively. Details on the growth process and AlN substrate preparation can be found elsewhere. [14], [15] All the samples were following the same general structure: a 150 nm thick $Al_{0.65}Ga_{0.35}N$ waveguide was

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grown on bulk AlN, followed by the growth of $Al_{0.55}Ga_{0.45}N$/AlN MQW, which were capped with 4 nm AlN. To decrease non-radiative recombination centers, a high V/III ratio of 2000 was used during the growth to reduce unintentional carbon point defect incorporation. Four samples were grown with different quantum well width of 2 nm, 2.5 nm, 3 nm, and 6 nm. X ray diffraction (XRD) and high resolution cross-section transmission electron microscopy (TEM) imaging were conducted to demonstrate the high quality of the laser structure growth and determine Al composition, well and barrier width of the AlGaN MQW. [2] Figure 1 shows the XRD result of AlGaN MQW laser with 6 nm well width design. As shown, the simulation curve shows good agreement with the XRD result. Very clear MQW fringes are observed, which indicates a sharp and well-defined interface between the well and barrier. The well and barrier width estimated by the XRD simulation are around 6 nm and 3 nm, respectively, which is consistent with the targeting well and barrier width. Then, photoluminescence (PL) spectral and laser threshold measurement were conducted on these samples to record the surface and edge emission spectra, respectively. The optical measurements were performed at room temperature (300 K) under a pulsed ArF excimer laser (λ=193 nm) along with a Princeton Instruments Acton SP2750 0.75 m monochromator with 150 grooves/mm grating, and a PIXIS: 2KBUV cooled charge-coupled device camera via optical fiber.

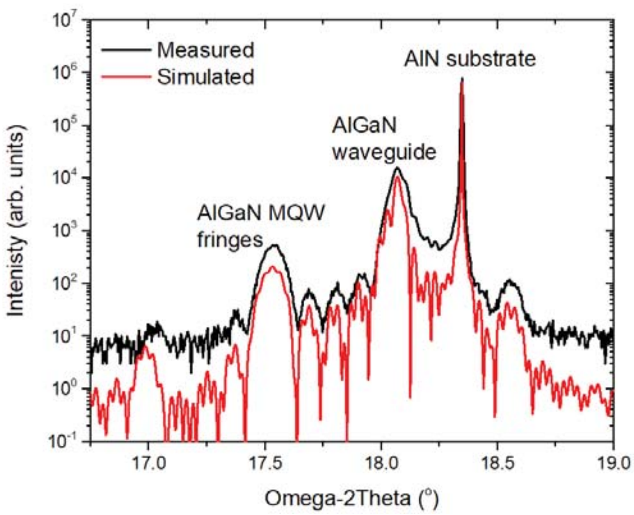

Figure 1: XRD of AlGaN MQW laser with 6 nm well width.

III. Results and Discussion

Figure 2 shows the PL spectral and the recorded laser threshold of four MQW samples with different well width. As seen, all four samples have quantum well emission between 240 nm and 260 nm. The emission peak (energy, eV) increases when quantum well width narrows. This is due to a strong quantum confinement in a narrow quantum well. Moreover, the full-width-half-maximum (FWHM) significantly increases for a wider quantum well. It is observed that the 6 nm well width sample has a FWHM=0.3 eV, compared to 0.2 eV in other three narrower quantum wells. Figure 2(b) also shows the laser threshold as a function of quantum well width. The lowest laser threshold of 5 kW/cm^2 is achieved for the 3 nm quantum well sample. It worth noting that the increase of the laser threshold in the wide quantum well (6 nm) is due to the strong QCSE. In the wide quantum well, a large separation between electrons and holes significantly decreases the overlap of their wavefunctions and reduces the dipole matrix element. Interestingly, it is also observed that the threshold also increases when the quantum well is thinner, which is similar to the results reported by Chow et al in InGaN laser. [12]

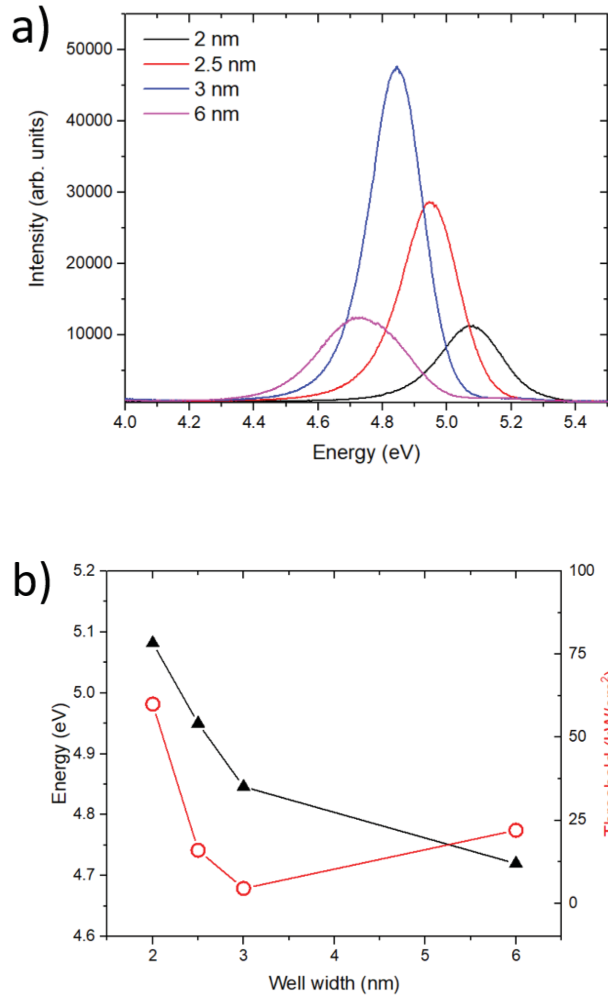

Figure 2: a) Photoluminescence (PL) results of samples with different quantum well width; b) the peak energy and threshold power as a function of quantum well width.

This increase of the threshold in the thin wells is likely due to two factors: 1) A thin active region reduces the overlap of the gain region (MQW) with the optical mode (reduced Γ-factor) and causes the threshold to increase; 2) A strong carrier confinement in the thin quantum well will increase the spontaneous recombination rate. Then, as indicated by Chow et al [12], fast spontaneous recombination will consume the carriers and increase the threshold carrier density needed to realize the positive gain in the laser cavity.

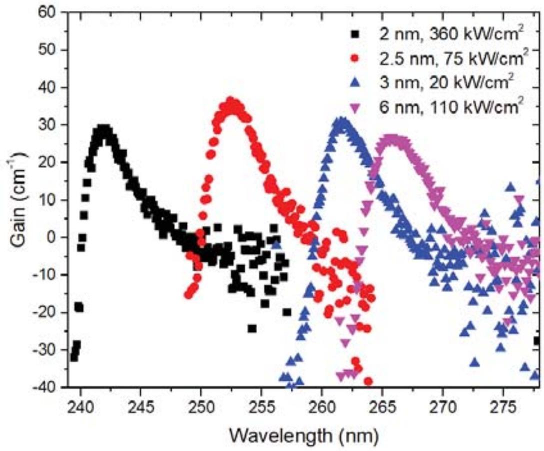

Figure 3: the gain spectrum for four samples with different quantum well width of 2 nm, 2.5 nm, 3 nm, and 6 nm.

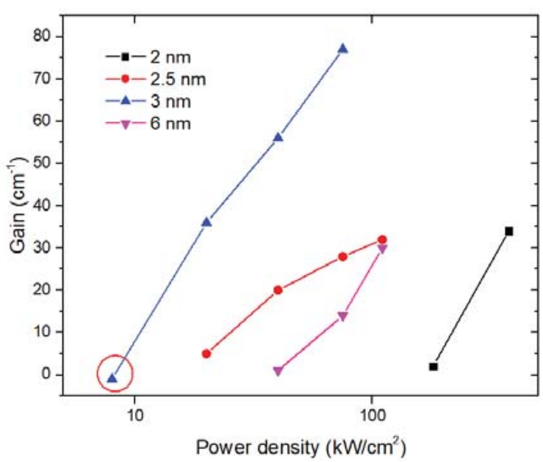

Figure 4: optical gain as a function of excitation power density for different samples. The threshold gain is 120 kW/cm^2, 15 kW/cm^2, 7 kW/cm^2, and 60 kW/cm^2 for 2 nm, 2.5 nm, 3 nm, and 6 nm well width sample.

The gain for all samples was measured using variable stripe length (VSL) method. More details on this measurement can be found elsewhere. [16] As seen in Figure 3, the gain spectrum was measured with the excitation power around 4-5 times of the threshold power. All four samples exhibit similar shape of the gain spectrum. From the low energy tail of the spectrum, the absorption coefficient is estimated to be around 10 cm^{-1}, which is similar to previously reported values. [16] However, to achieve a comparable gain around 30 cm^{-1}, 2 nm quantum well needs 20x times higher pumping power compared to 3 nm quantum well. Figure 4 shows the optical gain as a function pumping power density. The power to achieve positive gain is 120 kW/cm^2, 15 kW/cm^2, 7 kW/cm^2, and 40 kW/cm^2 for 2 nm, 2.5 nm, 3 nm, and 6 nm well width sample, respectively. These results show good agreement with the laser threshold measurement result shown in the Figure 2. Finally, it is pointed out that the highest gain of 80 cm^{-1} is achieved in the 3 nm well-width sample, which has the lowest threshold of 5 kW/cm^2. This result is comparable to the gain values previously demonstrated in InGaN-based laser diodes that were later used for electrically-injected laser. [17]

IV. Conclusions

In summary, we have investigated the influence of the well width on the optical properties of Al-rich AlGaN lasers. It is found that laser threshold is significantly influenced by the quantum well design due to the QCSE. The laser threshold reaches the minimum value of 5 kW/cm^2 when the quantum well width is 3 nm. The result shows good agreement with the threshold gain measured by the VSL method.

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