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# Four-Well Highly Strained Quantum Cascade Lasers grown by metal-organic chemical vapor deposition

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**Abstract:** We demonstrate a novel four-well injectorless design with short wavelength (5.5 $\mu\text{m}$ ) and room temperature operation utilizing highly strained  $\text{Ga}_{0.35}\text{In}_{0.65}\text{As}/\text{Al}_{0.70}\text{In}_{0.30}\text{As}$  (0.8/-1.5%) quantum wells.

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**OCIS codes:** (140.5965) Semiconductor lasers, quantum cascade

## 1. Introduction

Quantum Cascade Lasers (QCL) have become the dominant source in the mid-infrared (3-10  $\mu\text{m}$ ) due to their flexibility in emission wavelength, large continuous-wave (CW) power, and compactness. Many portable gas sensing and infrared countermeasure applications also require low input powers and minimal cooling. Consequently much focus has been paid towards achieving higher wall plug efficiency (WPE) [1-3].

One key parameter for optimizing WPE is the voltage defect [2]. Recent work done on injectorless designs [4-5], has demonstrated low voltage defects between 30-80 meV as compared to  $\sim 120$  meV in traditional designs involving miniband injectors [1]. Furthermore, injectorless structures have also shown low  $J_{\text{th}}$  much less than 1  $\text{kA}/\text{cm}^2$  at 77K, and  $\sim 450$   $\text{A}/\text{cm}^2$  even at room temperature [4]. These low thresholds are most likely due to two benefits of the injectorless design which has a reduced number of subbands participating in transport and therefore populated with electrons. The benefits include fewer idling electrons that result in a lower absorption loss, and shorter transit times resulting in a larger fraction of electrons contributing to population inversion.

Taking the published five-well injectorless design one step further, we designed a four-well QCL to further reduce the number of subbands that may accommodate idling electrons, while also trying to maintain a low voltage defect. Due to the large electric fields, the structure required highly strained quantum wells for reduced thermionic emission and reduced tunneling into the continuum. Therefore, we utilized  $\text{Ga}_{0.35}\text{In}_{0.65}\text{As}/\text{Al}_{0.70}\text{In}_{0.30}\text{As}$  which provides an estimated conduction band offset (CBO) of 0.89 eV. Due to the large strain, 8 band  $\vec{k} \cdot \vec{p}$  software by NextNano was used to simulate the wavefunctions in Figure 1.

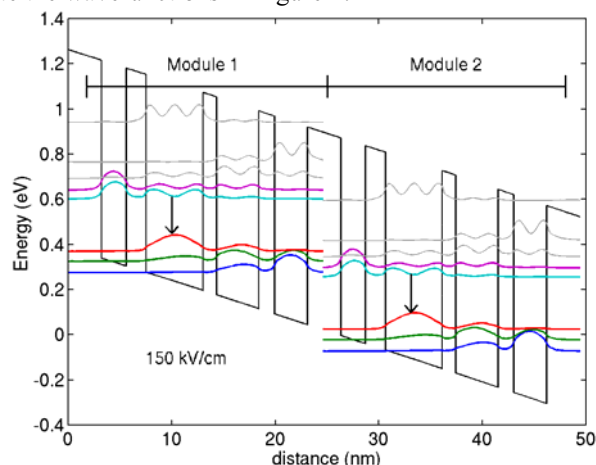


Figure 1. Band Diagram – QCL wavefunctions, electric field = 150 kV/cm, Module Length = 231 Å

## 2. Growth and Fabrication

To achieve high carrier confinement, highly strained quantum wells are grown from  $\text{Ga}_{0.35}\text{In}_{0.65}\text{As}/\text{Al}_{0.70}\text{In}_{0.30}\text{As}$ , corresponding to 0.8/-1.5% asymmetric strain, on InP substrate. The asymmetry of the strain was chosen to achieve

strain balance throughout the entire structure which has a larger fraction of  $\text{Ga}_{0.35}\text{In}_{0.65}\text{As}$ . The layer sequence of a single module in Figure 1 is the following, starting with the injection barrier 32/24/19/55/13/41/15/32 Å, where bold layers are  $\text{Al}_{0.7}\text{In}_{0.3}\text{As}$  and underlined layers are doped  $4.0 \times 10^{17} \text{ cm}^{-3}$ .

All layers are grown by MOCVD on N-doped InP substrate ( $\text{Si}, 2.5 \times 10^{18} \text{ cm}^{-3}$ ). The structure contains 45 modules in between a lower and upper waveguide cladding consisting of 300 nm of  $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$  ( $\text{Si}, 3.0 \times 10^{16} \text{ cm}^{-3}$ ) followed by 3  $\mu\text{m}$  of InP ( $\text{Si}, 1.0 \times 10^{17} \text{ cm}^{-3}$ ). A highly doped contact layer of 800 nm n-doped InP ( $\text{Si}, 8.0 \times 10^{18} \text{ cm}^{-3}$ ) is also grown after the top cladding.

The full laser structure is fabricated into ridge waveguides with widths of 4, 8, 14, and 20  $\mu\text{m}$  using ICP-RIE with PECVD deposited  $\text{Si}_3\text{N}_4$  etch mask. After ridge etching,  $\text{SiO}_2$  is deposited, top contacts holes are etched, and Ti-Au is sputtered. After substrate lapping and polishing, Ti-Pt-Au (50/50/50 nm) is sputtered for the back side contact.

### 3. Experimental Setup

The devices were mounted and placed in liquid nitrogen-cooled cryostat. Power measurements were performed in pulsed mode with 200ns at 1 kHz with a fast liquid nitrogen cooled HgCdTe detector. Power measurements were calibrated at room temperature utilizing an integrating sphere from Lapsphere. The electroluminescence linewidth of these devices were measured using a Nicolet FTIR with step scan module with  $16 \text{ cm}^{-1}$  resolution.

### 4. Results

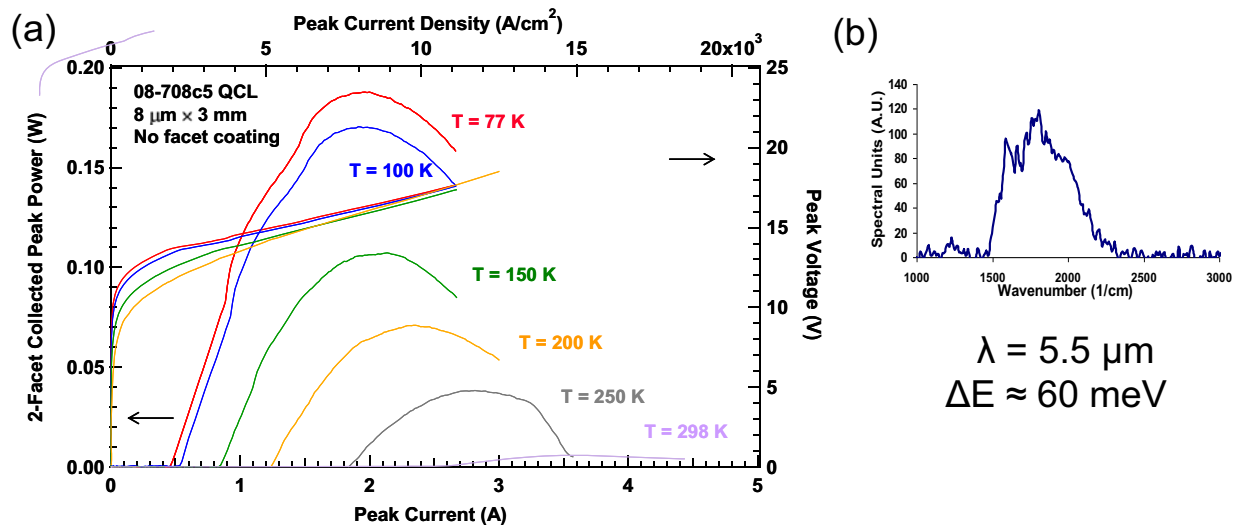


Figure 2. (a) Light-Current-Voltage (LIV) for 14  $\mu\text{m}$  3 mm long device (b) Electroluminescence from 14  $\mu\text{m}$  2 mm device at 77K

The devices operate in pulsed mode from 77-300K, with laser emission at  $\sim 5.5 \mu\text{m}$ ,  $J_{\text{th}} \sim 2 \text{ kA/cm}^2$  and a voltage defect of  $\sim 100 \text{ meV}$  at 77K. Furthermore, electroluminescence shows a linewidth of 60 meV.

### 5. Conclusion

We have demonstrated a novel four-well quantum cascade laser utilizing highly strained quantum wells with room temperature performance. This is the simplest QCL structure at mid-infrared wavelengths. Future work on reducing linewidths and possible leakage current should lead to better device performance in lasing threshold, operating temperatures, and output power levels.

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### 6. References

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