Injectorless Quantum Cascade Laser with very low voltage-defect grown by metal-organic chemical vapor deposition

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We demonstrate an $In_{0.66}Ga_{0.34}As/In_{0.355}Al_{0.645}As$ strain-compensated injectorless cascade laser; grown by MOCVD, with voltage defect ~30meV, which is much lower compared to heterogeneous injector cascade laser with 79meV[1] and conventional cascade laser with 140meV[2].

Quantum Cascade Laser (QCL) is a semiconductor laser that works based on intersubband transition [3]. It has already shown room temperature CW operation and high output power in mid-infrared region. Recently, much efforts focus on improving its low wall-plug efficiency. Significant improvement has been achieved through low optical loss waveguide structure, using anti-reflection coating on back facet, better active core design and superior growth, increasing the upper state LO-phonon non-raditive lifetime with quantum confinement Recently, a heterogeneous injector design has shown a significant improvement in terms of voltage defect, which directly related with wall-plug-efficiency [1]. Here we show, Injectorless QC-laser can go one step further in reducing voltage defect due to the absence of any highly- doped injectors in such design.

The injectorless-QCL structure presented in this paper is grown by low pressure MOCVD. The active region structure is similar to the design reported in ref 4, but with some modifications as described below. The layer sequence of one period is as follows, starting with undoped $In_{0.66}Ga_{0.34}As$ quantum well instead of a barrier as in original design, 6.5/*1.0*/5.0/*1.3*/**4.0**/***2.8***/**2.8**/*1.4*/1.2/*1.0*, with bold layers are averagely doped to $2.3x10^{16}$ cm^{-3} and $In_{0.355}Al_{0.645}As$ barrier layers are printed in italics. All layers are grown on N-doped InP substrate (Si, $2.0x10^{17}$ cm^{-3}). The injectorless structure has 60 active regions sandwiched between 500nm n-doped $In_{0.53}Ga_{0.47}As$(Si, $5.0x10^{16}$ cm^{-3}). The upper cladding consists of a 2.5µm n-InP (Si, $1.0x10^{17}$ cm^{-3}), followed by 800nm n-doped $In_{0.53}Ga_{0.47}As$(Si, $5.0x10^{18}$ cm^{-3}) and highly doped 200nm contact layer of n-doped $In_{0.53}Ga_{0.47}As$ whose doping has been changed nominal $3.0x10^{19}$ cm^{-3} from $1.0x10^{19}$ cm^{-3} .

After in-depth growth condition optimization, good material quality can be demonstrated from epitaxial characterizations. In Figure 2, the experimental and simulated x-ray diffraction curves of strain balanced injectorless QCL are given. The appearance of numerous sharp and narrow satellite peaks indicates the excellent interface quality between growth materials. The zeroth peak is InP substrate peak and experimental results fitted pretty well with simulation results.

The growth structure is defined into double heterostructure (DH) by photolithography with varying widths ranging from 10 to 25µm. Mesa is formed with wet etching using $HBr:H_2O_2:H_2O$ (20:3:100). Second photolithographic mask forms the opening pattern on PECVD deposited 300nm Si_3N_4.Top contact is formed with Ti/Pt/Au (20/50/500 nm) and after polishing, back contact is formed with Ge/Au/Ni/Au (12/17/25/300 nm).

The output power and applied voltage versus current (L-I-V) characteristics is obtained with the mounted device placed on a temperature-controlled cold finger of a nitrogen-cooled cryostat. Power measurements were performed on various laser devices up to 300K, in pulsed mode with a pulse width of 100ns and a repetition frequency of 1KHz. The detector was a liquid nitrogen cooled fast HgCdTe detector with a ~15nsec rise and fall time. Figure 1 shows the L-I-V curve. At 77K laser works at 5.8µm with a threshold current density of $1.1KA/cm^2$. Using, I-V data at 77K and assuming that the entire voltage drops occur over the active region only, a voltage defect of as low as 30meV is calculated. This reduction is due to the absence of any doped injector region inside the core laser design where significant voltage drops can occur. Lower voltage defect resists the waste of power as heat, which helps increasing the laser wall-plug efficiency. Threshold current density, J_{th}, as a function of heat sink temperature has been plotted and fitted with $J_{th}=J_0Exp[T/T_0]$ and it gives a characteristic temperature value of 160K. Injectorless QC- design also has a reduced optical power loss in the core for free carrier absorption.

We have demonstrated an injectorless QC-laser that has significantly low voltage defect of ~30meV. It promises a significant increase in wall-plug efficiency compared to other QC-laser.

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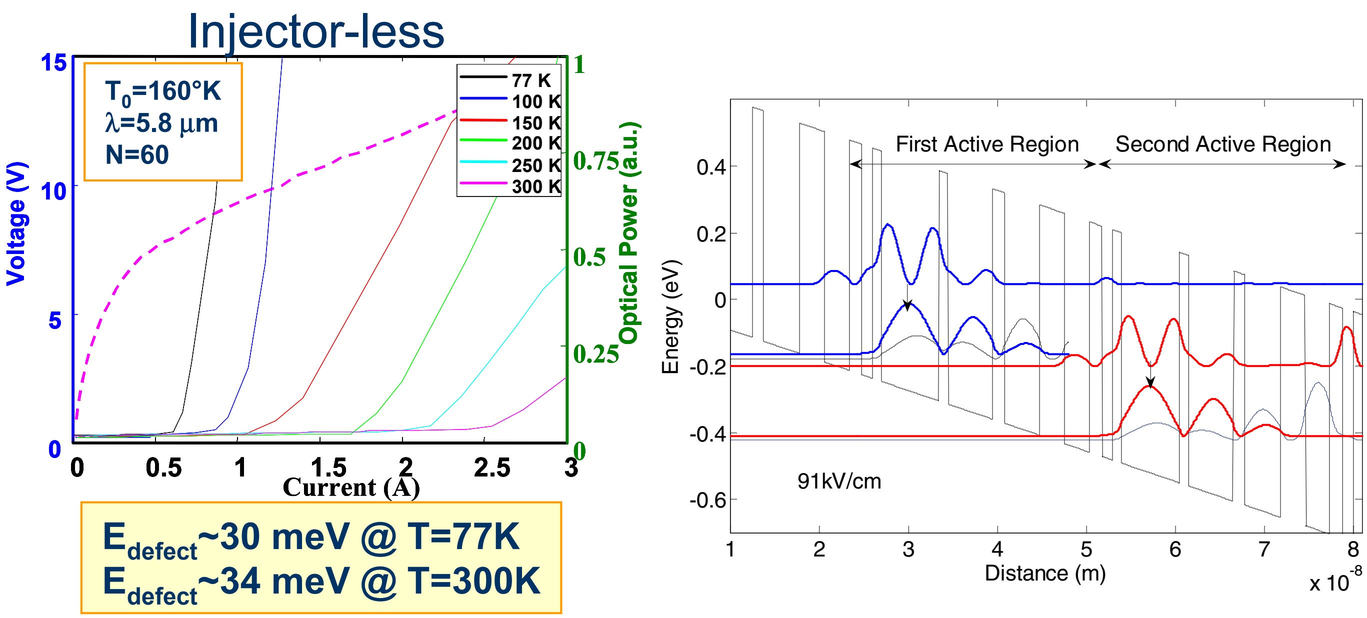

Figure 1 – (a) Light-current-voltage (L-I-V) measurement for a 2.1mm long and 25µm wide laser chip at different heat-sink temperatures (b) Band diagram for injectorless QCL at applied voltage of 91kV/cm showing the transition

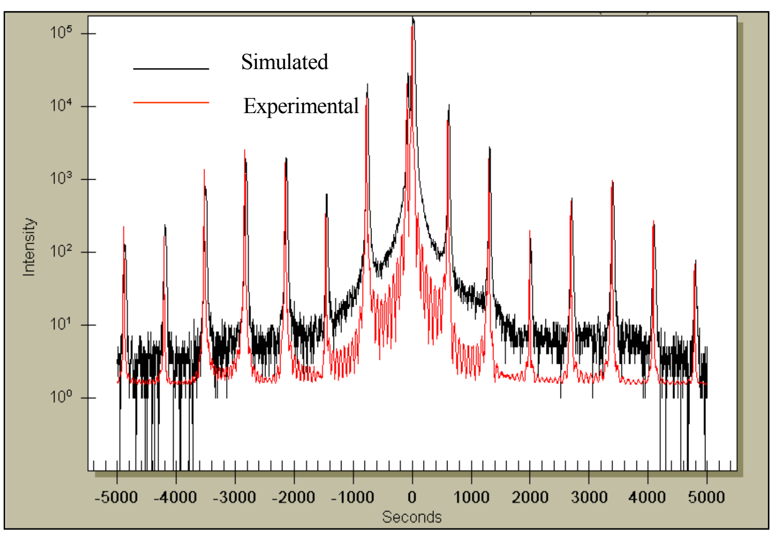

Figure 2 – (a) Experimental and simulated x-ray diffraction curve of a strain-balanced injectorless QC-laser