Improved Voltage Efficiency in Quantum Cascade Lasers

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Abstract: Improvements in quantum cascade laser wall-plug efficiency are pursued, with an emphasis on voltage efficiency. Parasitic series voltage is reduced by 83% via rapid thermal annealing. A quantum cascade laser is designed with a low voltage defect and short injector for high wall-plug efficiency operation. Results for the first generation design are promising, with a voltage efficiency of 79% at threshold and 69% at peak performance.

1. Introduction

Efficient use of power in a quantum cascade (QC) laser is of critical importance for a diverse array of applications. From environmental sensor networks to handheld medical diagnostics to infrared countermeasures, high wall-plug efficiency (WPE) is essential where power, temperature, weight, and space constraints exist. This work aims to improve WPE in these devices, with particular emphasis on voltage efficiency. Wall-plug efficiency in a QC laser can be defined as:

$$\eta_{wp} = \left(\frac{E_\gamma n_p}{n_p(E_\gamma + E_\Delta) + qV_s} \right) \left(\frac{\alpha_m}{\alpha_w + \alpha_m} \right) \left[\left(\frac{\tau_{up}}{\tau_{up} + \tau_{inj}} \right) \left(\xi_{inj} \right) \right] \left(\frac{J - J_{th}}{J} \right)$$

With voltage efficiency defined as:

$$\eta_v = \left(\frac{E_\gamma n_p}{n_p(E_\gamma + E_\Delta) + qV_s} \right)$$

Where E_γ is the photon energy, n_p is the number of active region periods, E_Δ is the voltage defect per period, V_s is the series voltage, α_m is mirror loss, α_w is waveguide loss, τ_{up} is the effective upper state lifetime, τ_{inj} is the effective injector lifetime, ξ_{inj} is the injection efficiency, and J_{th} is the threshold current density. By reducing V_s and E_Δ in this work, voltage efficiency can be improved to 69% at the peak WPE operating point, an improvement over the 62% reported for state-of-the-art high efficiency designs [1]. This work also features a short injector in the quantum design, with four well/barrier pairs, as compared to the conventional design, which has seven well/barrier pairs. This shorter injector is expected to result in lower threshold currents, higher maximum currents, and shorter injector transit time (τ_{inj}).

2. Reduced Contact Resistance

In a QC laser, the majority of the voltage drop occurs over the active core. This voltage drop can be attributed to two sources – the laser transition (i.e. the photon energy) and the energy drop necessary to depopulate the lower laser level and inject electrons into the upper laser level of the next active region (i.e. the voltage defect). Any other voltage dropped in the laser structure is undesirable and can be considered "parasitic." Due to mechanisms such as a highly doped InGaAs top contact layer and digital gradings between materials with differing conduction band potentials, most of this parasitic voltage drop is expected to exist in the metal-semiconductor junction of the substrate-side contact.

For this work, an "empty" structure was grown containing all of the layers found typically in a QC laser with the exception of the active core. This material was processed into a mesa with varying top and bottom contacts. Top contacts used were Ti(20nm)/Au(300nm), Ge(20nm)/Au(300nm), and Ni(25nm)/Ge(20nm)/Au(250nm), deposited via e-beam evaporation. Bottom contacts used were Ge(20nm)/Au(300nm) and Ni(25nm)/Ge(20nm)/Au(250nm). Some samples were annealed, with anneal temperatures ranging from 375°C to 450°C and times ranging from 30s to 60s. Current-voltage measurements were taken with a 4-probe set-up under continuous wave, room temperature operation. A negative applied bias was used, as is typical in full QC structures. From Figure 1, we can see that a certain amount of parasitic voltage is dropped across a QC structure with conventional processing (Ti/Au top and Ge/Au bottom contacts without annealing). However, this voltage can be greatly reduced by rapid thermal annealing, with a 0.52V reduction at a typical operating current density, resulting in an 83% reduction in total parasitic voltage. Varying contact metallization does not have a significant effect in enhancing this reduction. This voltage reduction from annealing was also demonstrated in actual QC lasers, with a reduction of 0.2V to 0.3V.

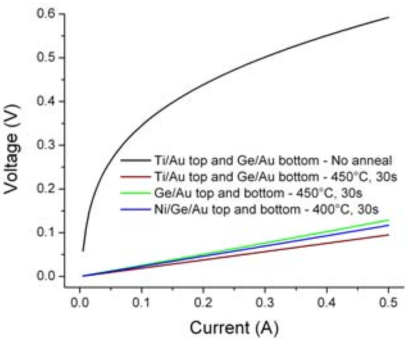

Figure 1: Voltage-current curves for "empty" structure under continuous wave, room temperature operation. The baseline uses unannealed Ti/Au top and Ge/Au bottom contacts. The vast reduction in parasitic series voltage by rapid thermal annealing can be seen.

3. Low Voltage Defect, Short Injector QC Laser

A new QC laser was designed (Figure 2a) featuring a low voltage defect and short injector. The low voltage defect is expected to improve voltage efficiency. The injector length reduction, from seven well/barrier pairs in a conventional QC laser [1] to four in this design, should result in a lower threshold current density due to increased gain, a higher maximum current density and lower differential resistance due to a reduction in the time to transit a period, and an improvement in internal efficiency due to electrons spending a larger percentage of their time in the upper state of the lasing transition.

Once grown, the wafer was processed into a ridge laser and annealed at 400°C for 30s before mounting. The pulsed light-current-voltage characteristics for this device can be seen in Figure 2b. The 80K threshold and voltage defect are indeed very low, with J_{th}=220A/cm^2 and E_Δ=65meV at threshold. However, the maximum current density is rather low as well (J_{max}=2.55kA/cm^2), with an overall 80K peak WPE of 11.1%. Peak 80K continuous wave WPE is 8.6% for this device. Temperature performance is described by a pulsed T_0=117K at high temperatures. Based on "1/L" measurements, this laser has a waveguide loss of 3.1cm^{-1}. The peak pulsed WPE of 11.1% can be further broken down into optical efficiency (57.8% for a 3mm long, as-cleaved device), internal efficiency (37.7%), current efficiency (73.6%), and voltage efficiency (69.2%). The particularly low value for internal efficiency led us to take a closer look at our quantum design model. After correcting the material parameters in the model, a comparison between the model and electroluminescence data reveals that electrons are being injected into the state above the upper laser level, something we are currently working to correct.

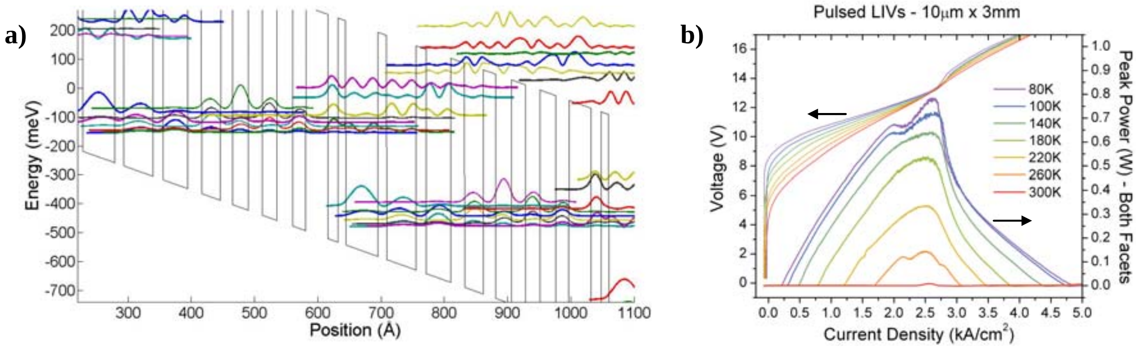

Figure 2: (a) Conduction band diagram for a novel low voltage defect, short injector QC laser. **(b)** Pulsed light-current-voltage characteristics for this design taken at different temperatures.

4. Conclusions

Efforts were undertaken to improve QC laser wall-plug efficiency, with a particular emphasis on voltage efficiency. Via rapid thermal annealing, parasitic series voltage was reduced by 83%. A novel QC laser, featuring a low voltage defect and a short injector, was designed and characterized. The low voltage defect, combined with annealing, results in an improvement in voltage efficiency over the state-of-the-art from 62% to 69%. Furthermore, low threshold current densities and low waveguide loss show promise for improved overall WPE. With a correction in the quantum design model and a redesign, this new QC laser is expected to show good wall-plug efficiency performance.

This work is supported in part by DARPA-EMIL and MIRTHE (NSF-ERC).

5. References

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