Low Voltage Defect Heterogeneous Quantum Cascade Laser

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Abstract: We demonstrate a quantum cascade laser employing two different injector regions and matched 4.6μm optical transitions for low-voltage-defect operation. The laser has a pulsed wall-plug efficiency of 19% at 80K and operates pulsed at 300K.

OCIS codes: (140.5965) Semiconductor lasers, quantum cascade; (140.3070) Infrared and far-infrared lasers

1. Introduction

Since the invention of the quantum cascade (QC) laser, rapid progress in laser performance has made these devices a viable mid-infrared source for many scientific and commercial applications. One of the main technological and commercial challenges that has yet to be adequately addressed is the creation of lasers with large wall-plug efficiency (WPE). Here, we present a design approach to increasing the WPE by reducing the "voltage defect," or the energy drop per stage that does not contribute to the generation of light. Adapting a strategy that was previously applied to the active region of QC lasers [1], we design, fabricate and characterize a single-wavelength, heterogeneous QC laser that uses two types of injectors to achieve low voltage defect operation [2]. There is a trade off in laser performance between thermal backfilling of the lower laser level and voltage defect. The two different injectors are designed to optimize both throughout the structure, in particular the low-voltage defect injector remains undoped.

2. Active core design and device fabrication

A portion of the active core conduction band diagram is shown in Fig 1(a). The QC laser structure was grown by molecular beam epitaxy (MBE) on InP substrate using strain-balanced $In_{0.678}Ga_{0.322}As/Al_{0.635}In_{0.365}As$ and consists of a low-loss waveguide surrounding 17 repeats of a doped injector – active region – undoped injector – second active region sequence. The doped injector region (A in Fig. 1(a)) is of conventional design and has a voltage drop designed to minimize both thermal back-filling of the previous lower laser level and voltage defect. The following active region is a single phonon resonance design and has a calculated transition energy of 283 meV. The undoped injector region (B in Fig. 1(a)) is engineered to minimize the voltage defect and provide efficient extraction of electrons from the previous active region. The active region following the undoped injector is a two phonon resonance design [ref] and has an identical design transition energy to the single phonon active region. The average voltage defect of the active core is 71 meV per injector-active region pair, about half that of a conventionally designed laser.

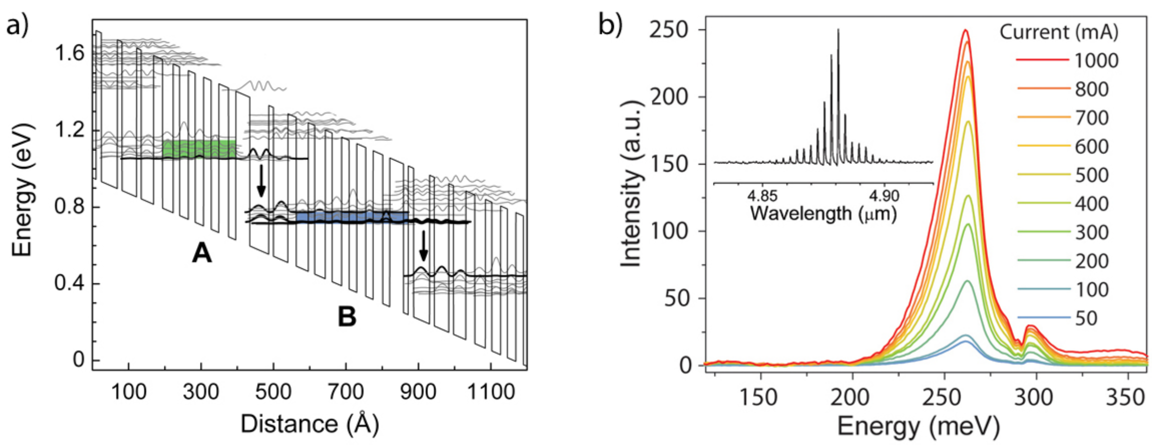

Fig. 1. a) A portion of the conduction band diagram with the moduli squared of the relevant wavefunctions for an applied field of 82 kV/cm. The doped and undoped injector regions are marked by the letters A and B respectively and the shaded green and blue regions show the voltage defect of the two injector regions. The optical transitions are marked by the vertical arrows and have identical transition energies of 283 meV. b) Pulsed electroluminescence spectra from cleaved mesas at 80 K for a range of pumping currents. The inset shows the room temperature lasing spectrum.

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Electroluminescence (EL) structures were fabricated as deep-etched, 200 μm diameter mesas with Ti/Au (250/2500 Å) top and Ge/Au (250/2500 Å) bottom contacts. The mesas were cleaved approximately along the diameter and mounted to

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a copper heat sink. Lasers were fabricated as deep-etched ridge waveguide lasers with SiN_x (3300 Å) for side-wall electrical insulation. The devices were thinned to ~200 μm and top Ti/Au (250/2500 Å) and bottom Ge/Au (250/2500 Å) contacts were deposited. The ridges were cleaved to various lengths and mounted to copper heat sinks epitaxial side up. Several devices were also high-reflectance (HR) coated on their back facet using SiO_2/Ti/Au/SiO_2 (4000/150/1500/1000 Å).

3. Device characterization

EL spectra were collected for a wide range of pumping currents at several heat sink temperatures. Figure 1(b) shows measurements at 80 K. The EL spectra all have a single peak and closely resemble those of a homogeneous QC laser despite the active core being comprised of two different active region designs. The slight asymmetry on the low-energy side of the peak is attributed to a small misalignment of the two optical transitions. This misalignment, even though it is small, will adversely affect laser performance and will be addressed in future generations of the design.

Light-current-voltage (LIV) measurements were performed on many lasers ridges at several heat sink temperatures. Figure 2(a) shows LIV data as a function of temperature for an as-cleaved 15 μm x 1.23 mm laser. The laser has a threshold current density of 1.2 kA/cm^2 and produces a peak power of 2.0 W. Using the current-voltage curve at 80 K and allowing for a 0. 5 V drop due to contact and waveguide resistance, an average voltage defect of 64 meV is extracted. This value is in good agreement with the calculated value 71 meV. Fitting an exponential curve to the threshold current density, J_{th}, as a function of temperature, $J_{th} = J_o{*}exp(T/T_o)$, gives T_o = 140 K. Laser performance was also characterized as a function of cavity length. Figure 2(b) plots pulsed WPE versus cavity length for several devices. The black squares represent as-cleaved lasers and the red triangles represent select lasers that were HR coated on the back facet. The best performing as-cleaved laser, 15 μm x 1.44 mm, had a WPE of 14 % per facet. A 15 μm x 2.3 mm laser with an HR coating on the back facet had a maximum WPE of 19 %. The decrease in WPE for lasers shorter than ~1.5 mm is attributed significant increases in $J_{th.}$ For longer lasers, the decrease is due to a reduction in the extraction efficiency as waveguide loss becomes the dominant loss mechanism. Using length-dependent threshold current density data, a waveguide loss of 3.9 ± 0.1 cm^{-1} is extracted.

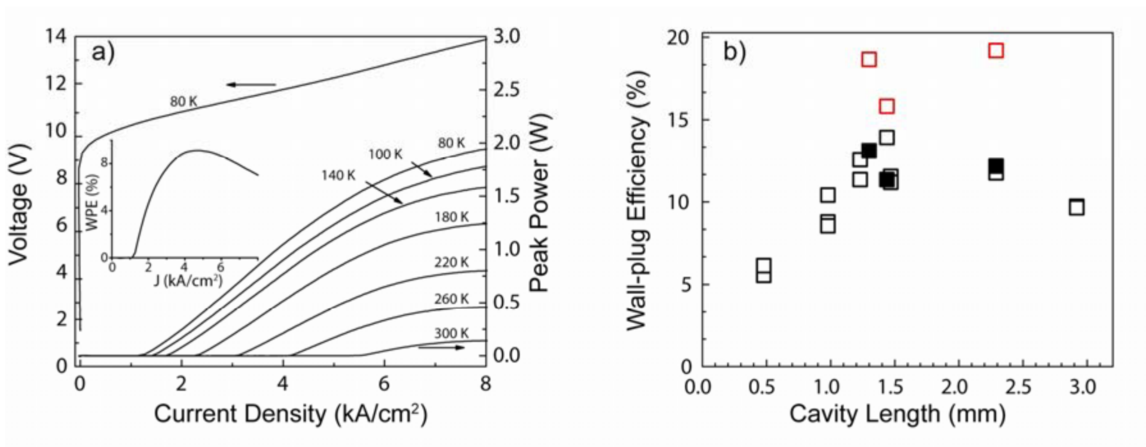

Fig. 2. (a) Pulsed light-current-voltage measurements for a 15 μm wide, 1.23 mm long laser at different heat sink temperatures. The current-voltage curve is for 80 K. The inset shows WPE vs current density, *J*, at 80 K. (b) Peak, pulsed wall-plug efficiency per facet versus cavity length for laser ridges of various widths. The black squares are for uncoated devices and the red squares are for select lasers (fill-in black squares) that were high reflectance coated and re-measured.

4. Conclusions

We have designed and characterized a QC laser with a heterogeneous active core that consists of two alternating injector regions and matched optical transitions that operates with an average voltage defect per period of 64 meV; approximately half of conventional designs. Lasers operate in pulsed mode up to room temperature and have a peak WPE of 19 % at 80 K. Such active core designs may be an effective approach to increasing the WPE of QC lasers.

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

6. References

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