# Low-Voltage Defect Quantum Cascade Laser with Heterogeneous Injector Regions

Anthony J. Hoffman, Stephan Schartner, Scott S. Howard, Kale J. Franz, Fred Towner, and Claire Gmachl

***Abstract*—We demonstrate a quantum cascade laser that uses two alternating injectors with matching 4.6 µm active regions that operates in pulsed mode up to room temperature with a peak wall-plug efficiency of ~10 %.**

## I. Introduction

THE intrinsically large design space for quantum cascade (QC) lasers has lead to many innovative devices [1]. These advances have resulted in lasers that operate in continuous wave at room temperature [2], devices with broadband tuning capabilities [3], and lasers with multi-wavelength emission [4-7]. In particular, a class of multi-wavelength QC lasers is based on a stack of heterogeneous active regions and injectors. In these lasers, multiple optical transitions with different energies are designed and either stacked [6] or interdigitated [7]. While previously this concept was applied to active regions, here we focus on QC lasers with heterogeneous injectors. We use this approach to increase the wall-plug efficiency of the QC laser by decreasing the "voltage defect". Similar to diode lasers, voltage defect in a QC laser is the energy per stage which does not contribute to the generation of light, i.e. the energy difference between the lower laser level of one active region and the upper laser level of a subsequent downstream active region.

## II. Experiment

A portion of the heterogeneous QC laser active region is shown in Fig. 1; the wafer was grown by molecular beam epitaxy on InP substrate using strain compensated $Al_{0.635}In_{0.365}As/In_{0.678}Ga_{0.322}As$. The conduction band consists of two active regions of nominally identical transition energies, 280 meV, interleaved with two injector regions of different design. The first injector is a conventional, doped QC laser injector region with a voltage drop that is selected to minimize thermal backfilling of the lower laser level of the preceding active region and simultaneously minimize the voltage defect. The second injector is undoped and is engineered to minimize only the voltage defect while still providing efficient extraction of the electrons from the previous active region. The basic structure consists of an undoped injector - active region - doped injector - second type active region. This is repeated 17 times and is surrounded by a low loss waveguide.

The samples were fabricated into circular mesas and deep-etched ridge waveguide lasers. The mesas were ~200 µm in diameter with top Ti/Au electrical contacts. The samples were thinned to ~200 µm and Ge/Au was deposited for the back side contact. For testing, the mesas were cleaved roughly along the diameter and mounted to a Cu heat sink. The ridge lasers, which varied in width from 12 – 23 µm, were fabricated using wet chemical etching and $SiN_x$ for electrical insulation. Ti/Au and Ge/Au were used for top and back contacts respectively. Laser bars ranging from 0.5 – 3.5 mm lengths were cleaved, mounted epilayer up on a Cu heat sink, and wire bonded.

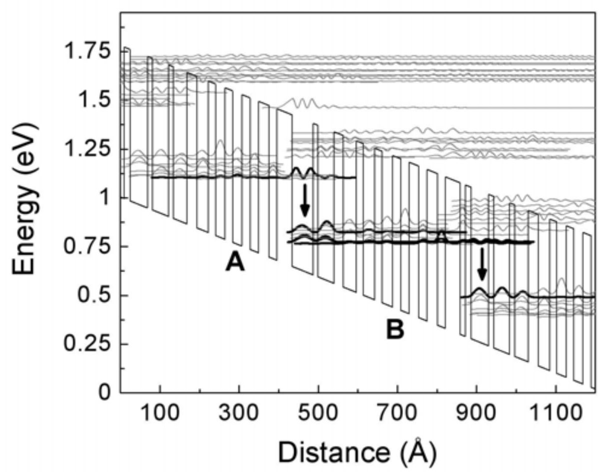


Fig. 1: A portion of the conduction band structure with the moduli squared of the relevant wavefunctions. The doped injector region is marked by **A** and the undoped injector region is marked by **B**. The black vertical arrows indicate the optical transition with calculated energies of 280 meV. The calculations are for an applied electric field of 82 kV/cm.

A. J. Hoffman, S. H. Howard, K. J. Franz, A. Sridhar, and C. Gmachl are with the Dept. of Electrical Engineering, Princeton University, Princeton, NJ 08544 USA (email: ajhoffma@princeton.edu).

S. Schartner is with the Center for Micro and Nanostructures, TU Vienna, Vienna, Austria; he was a visiting researcher at Princeton University.

F. Towner is with Maxion Technologies, Inc., Hyattsville, MD 20782

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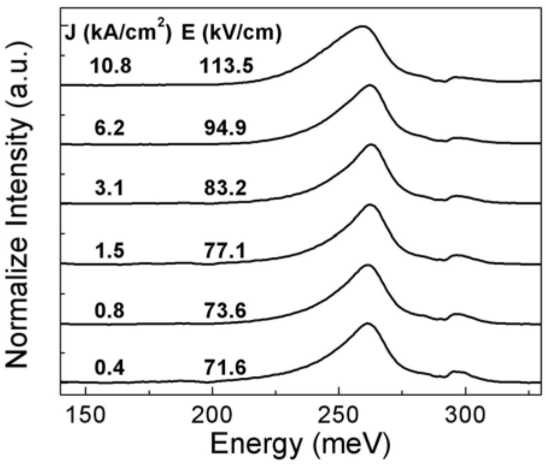


Fig. 2. Normalized electroluminescence (EL) spectra from cleaved mesas measured at different values of applied electric field. The two different active regions appear as one emitter.

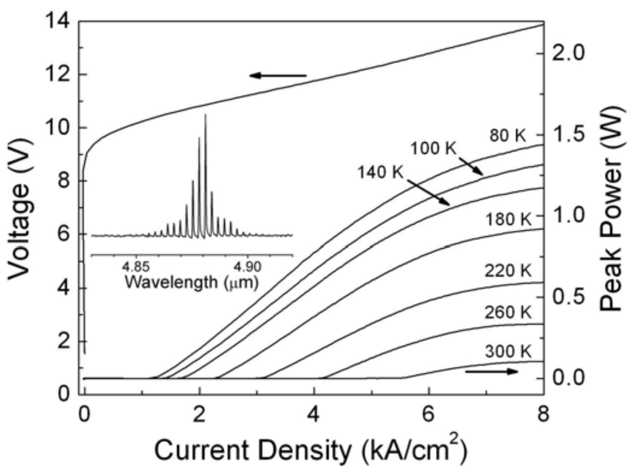


Fig. 3. Pulsed light-current measurements of a 15 μm wide, 1.23 mm long laser at different heat sink temperatures. The current-voltage curve for 80 K is also plotted. The inset shows a room temperature spectrum for the same laser.

## III. RESULTS

Pulsed electroluminescence (EL) from the cleaved mesas with varying electric field was examined from 80 K to room temperature using a Fourier transform infrared spectrometer (FTIR) operating in step-scan mode with a cooled HgCdTe detector. Figure 2 shows EL results for measurements taken at 80 K. Despite using two different active region designs – albeit at the same wavelength – in its active core, the structure displays an EL spectrum not noticeably different from homogeneous QC lasers.

Figure 3 shows light-current measurements for a 15 μm wide, 1.23 mm long laser ridge obtained using 80 ns current pulses at 5 kHz for different heat sink temperatures. The current-voltage curve for 80 K is also shown. A peak pulsed power of 1.5 W was obtained with a threshold current density of 1.2 kA/cm$^2$. The peak efficiency at 80 K for this laser occurs at a current density, $J_{peak}$, of 4.6 kA/cm$^2$ and is 9.3% measured for one facet. As the temperature is increased, $J_{peak}$ increases and the peak efficiency decreases. At room temperature $J_{peak}$ is 7.4 kA/cm$^2$ and the efficiency is 0.6 %. Using the light-current-voltage data at 80 K, the *average* voltage defect is calculated as 74 meV per injector-active region pair.

Time-integrated emission spectra were also measured as a function of injection current and heat sink temperature. The inset of Fig. 3 shows a characteristic room temperature lasing spectrum using 100 ns pulses at 80 kHz.

## IV. CONCLUSIONS

We have demonstrated a heterogeneous QC laser that uses two different types of injector regions to reduce the voltage defect of the device. Such designs may be an effective approach to increasing the wall-plug efficiency of QC lasers.

## V. ACKNOWLEDGEMENTS


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