Negative Differential Resistance and Pulse Instabilities in Minimalized Quantum Cascade Laser Structures

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Abstract: We study high performing mid-infrared quantum cascade lasers with highly discretized injector regions. We observe negative differential resistance features of ~2V that persist to room temperature and pulse instabilities below 180K.

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1. Background

The conventional quantum cascade (QC) injector region was born with the laser's first demonstration in 1994 [1]. Using a series of roughly 6 – 8 quantum wells, a dense manifold of energy states extracts electrons from the lowest states of one active region and funnels those electrons into the upper laser state of the next active region. Rarely have QC designs departed from this conventional model of an injector region [2].

Here, we examine the properties of injectors functioning with highly discreet energy states. We consider three and two quantum well injector regions that support 125 meV of energy defect between successive photon transitions. We find properties reminiscent of the Esaki and Tsu superlattice [3]—such as negative differential resistance—that spawned the field of superlattice device engineering many decades ago. In the devices reported here, these effects are all the more complex due to the nonlinear inclusion of stimulated emission in the overall device behavior. Even with these features, laser performance is comparable with today's high performance devices: low temperature thresholds are in the range of 500 A/cm^2 and room temperature peak output power is ~2 W.

2. QC laser design & fabrication

We designed highly "minimalized" QC laser structures that support photon emission at 241 meV (λ = 5.1 μm) and energy defects between successive active regions of 125 meV. Two structures are studied—"3-well" and "2-well" injectors—which respectively total 6 and 5 quantum wells for the entire QC period. The band structures, as shown in Fig. 1, have total period lengths of 309 and 275 Å, respectively; this is in contrast to > 500 Å for the best conventional laser structures. The primary difference between the two designs is the number of injector states; specifically, the two-well injector structure (Fig. 1b) lacks the third injector state of the three-well injector structure (red, indicated by an arrow in Fig. 1a). These devices were grown with metal-organic vapor phase epitaxy and fabricated into conventional ridge and buried heterostructure lasers. Electroluminescence (EL) mesas without optical feedback were also analyzed. In all cases, data reported is for low duty cycle pulsed measurements.

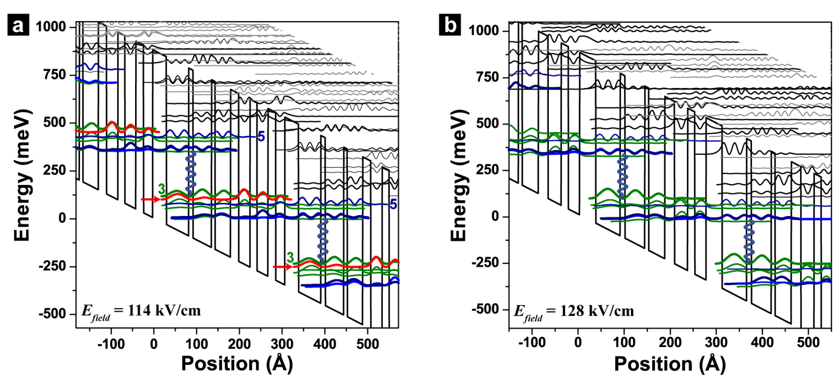

Fig. 1. (a) Three-well injector QC laser design. Optical transitions of 241 meV are indicated by wavy arrows. A single stage of the QC layer sequence is (in angstroms starting from the injection barrier) **32**/52/**10.5**/43/**8.5**/36/**16**/<u>27</u>/<u>**16.5**</u>/<u>26</u>/<u>**18**</u>/<u>21.5</u>, where $In_{0.29}Al_{0.71}As$ barriers are in bold and $In_{0.64}Ga_{0.36}As$ wells are in normal font. Underlined layers are Si-doped n=1×10^{17} cm^{-3}. (b) Two-well injector QC laser design (241 meV optical transition). The layer sequence is **35**/53/**10.5**/43/**8.5**/35/**21**/<u>28.5</u>/<u>**15.5**</u>/<u>24.5</u>. Here, underlined layers are Si-doped n=1.4×10^{17} cm^{-3}.

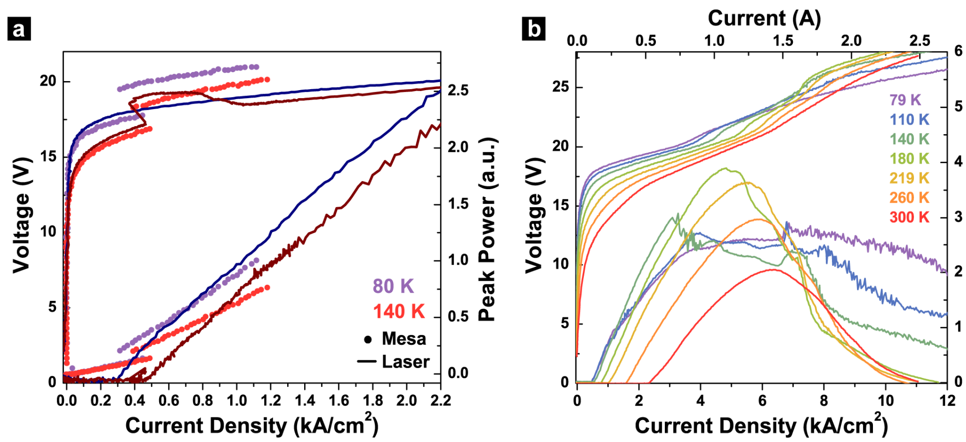

Fig. 2. (a) Light-current-voltage (LIV) data for 3-well injector structure EL mesa and laser devices. NDR features are seen for all temperatures in EL devices, but are seen in lasers only when threshold is above the NDR voltage onset. (b) LIV data for a 2-well injector laser showing power instabilities are seen at temperatures below 180 K.

3. Negative differential resistance

Pronounced negative differential resistance (NDR) is observed in the 3-well injector structure (Fig. 1a), shown in the Fig. 2a light-current-voltage (LIV) data. In EL mesas, we see a rapid 1.7 V (11 kV/cm) increase and an accompanying current reduction at current densities near 0.3 kA/cm^2. In laser devices, no NDR features are seen at the lowest measured temperatures (near 80 K). Rather, the NDR feature emerges near 140 K, and it then persists through room temperature. The 140 K temperature corresponds to the point where the laser threshold is greater than the current density at which the NDR is triggered. Thus, lasing suppresses the observed NDR. Furthermore, when the NDR feature is observed at elevated temperatures, a sufficient cavity photon density actively reduces the operating voltage to the pre-NDR band configuration. We attribute this to a shift in the electron distribution profile through the QC period as stimulated emission reduces the upper state lifetime. The NDR feature itself results from the presence of two rapid electron transport paths: one at the design field of 114 kV/cm as shown in Fig. 1a, and one at 103 kV/cm when state 3 in one active region is aligned with state 5 in the next active region.

4. Laser instabilities

Electric field profiles in QC structures are largely assumed to be homogenous when the doping density is low, or periodic but stable when the doping density is higher. However, charge instabilities have long been known to exist in superlattice structures [4]. Intuitively, charge instabilities can result when local disruptions of the current flow locally perturb the field, leading to field domains. The highly nonlinear event of lasing is expected to exacerbate this instability, and in these minimalized QC structure, we can observe these instabilities. The Fig. 2b LIV for the 2-well structure shows peak output at 180 K, while highly unstable pulse behavior at lower temperatures limits output power. The time evolution of the light pulse over the 100 ns period also indicates highly chaotic behavior. These instabilities are damped with increasing temperature, as is also common for traditional superlattice devices.

5. Conclusions

We have observed the “classical” superlattice behavior of negative differential resistance and instabilities in mid-infrared QC lasers. The behavior was observed in highly minimalized QC laser structures with QC periods of only 5 or 6 quantum wells, where injector regions comprise only 2 or 3 highly discrete energy states. These results confirm the expected behavior of QC lasers as tunneling devices, and at the same time show such behavior does not prohibit laser performance for short-period QC structures.

6. Acknowledgements

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7. References

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