Two-Dimensional Conduction-Band Engineering: Achieving Ultimate Wallplug Efficiency and Reliability for Quantum Cascade Lasers

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Dan Botez is Philip Dunham Reed Professor at the University of Wisconsin-Madison. He received his BS (1971), MS (1972) and PhD (1976) degrees in Electrical Engineering from University of California, Berkeley. In 1977 he joined RCA Labs, Princeton, where his research focused on new types of high-power, single-mode lasers, which allowed the first demonstration of high-data-rate optical recording with diode lasers and became the most powerful commercially available single-mode lasers during 1981-1985. In 1986 he joined TRW Inc., Redondo Beach, CA, where his research involved novel types of high-power, diffraction-limited phase-locked arrays. He is the co-inventor of the resonant-optical-waveguide (ROW) array concept, which represents the first Active-Photonic-Crystal (APC) laser structure for spatial-mode selection in wide-aperture (>100 μm) devices. As a result, in 1990 he led the team that “broke” the 1-W coherent-power barrier for diode lasers. At UW-Madison he has focused on high-power Al-free lasers and achieved record-high CW power and wallplug efficiency from near-infrared diode lasers. Recent work has focused on mid-infrared quantum cascade lasers (QCLs) which led to the first model for carrier leakage in QCLs, and the concepts of deep-well and tapered-active-region QCLs for highly temperature insensitive devices. He is a Fellow member of the IEEE and the OSA, and the recipient of the 2010 OSA Nick Holonyak Jr. Award.

Conventional quantum cascade lasers (QCLs) have device cores which are composed of a superlattice of quantum wells (QWs) and barriers of fixed alloy compositions, which, for short-wavelength (4.5-5.0 μm) devices, results in relatively small energy differences between the upper laser level and the top of the exit barrier: 150-250 meV.\(^1\) In addition, for 4.6-4.8 μm QCLs operated around room temperature (RT), the electrons in the injector and the upper laser level are found to have a higher temperature than that of the of the lattice;\(^1,2\) that is, they are hot. In turn, conventional, high-performance 4.5-5.0 μm-emitting QCLs suffer from severe carrier leakage, which results in low characteristic-temperature \(T_0\) values (130-150 K)\(^1,2\) for the threshold-current density, \(J_{th}\), and low characteristic-temperature \(T_1\) values (140-170 K)\(^1,2\) for the slope efficiency, \(\eta_s\), at heatsink temperatures above RT. As a result, the maximum wallplug efficiency, \(\eta_{wp,max}\) in CW operation at RT, for light emitted from the front facet of conventional devices with high-reflectivity-coated back facets, has typical values\(^1\) of only ≈13%, and no statistically relevant lifetest data have been reported to date for high-power CW devices. Furthermore, thermally accelerated lifetime studies have been limited to low CW powers (≤0.2 W);\(^3,4\) thus, no device-aging model can be arrived at for high-power (≥0.5 W) CW QCLs.\(^4\)

By employing the advantages in device design offered by the flexibility to control, via MOCVD crystal growth, the composition (and strain) of each layer within a QCL structure, we have been able to implement novel designs for the active regions of QCLs: the deep-well (DW) concept\(^1\) and the tapered active-region (TA) concept.\(^1,5\) DW QCLs have demonstrated significant suppression of carrier leakage, as evidenced by high \(T_0\) and \(T_1\) values: 253 K and 285 K, respectively, above RT.\(^1\) We have also proposed\(^1,5\) and demonstrated\(^1,6\) an improved DW QCL-active design for which the barrier heights increase in energy from the injection barrier to the exit barrier (Fig. 1); the so-called Tapered-Active (TA) design. Fig. 2 shows the conduction-band diagram and relevant wavefunctions for a fabricated DW TA QCL structure.\(^6\) Preliminary results are \(T_0\) and \(T_1\) values of 231 K and 797 K, of which the \(T_1\) value, the key signature of carrier leakage,\(^1\) represents a record-high value for QCLs. By using gas-source MBE growth and a TA-like active-region design, Bai et al.\(^7\) have obtained \(T_0\) and \(T_1\) values of 244 K and 348 K, respectively, for 4.9 μm-emitting QCLs of moderately high doping, as needed for high-power performance. As a result they achieved a record-high single-facet, RT CW wallplug-efficiency value of 21 %, still short of theoretically limits\(^8,9\) (i.e., ~30% at \(\lambda = 4.9 \mu m\)).

We have also developed\(^10\) a comprehensive model for the carrier leakage in QCLs which takes into account the effect of both inelastic scattering (i.e., LO-phonon assisted scattering) and elastic scattering (e.g., due to interface roughness). The model was validated in that it correctly predicted the \(T_0\) values for both conventional and DW QCLs. Thanks to it, we have shown\(^10\) that shunt leakage current via thermal excitation to the energy state right above the upper laser level

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(e.g., state 5 in Fig. 1) followed by relaxation to lower AR states (e.g., states 3, 2 and 1 in Fig. 1) is the primary carrier-leakage path. Then, for a given state-4 electronic temperature value, $T_{e4}$, the scattering rate is well approximated by:

$$\frac{1}{\tau_{45}} \approx \frac{1}{\tau_{54}} \exp \left( -\frac{E_{54}}{kT_{e4}} \right)$$

where $\tau_{45}$ is the lifetime corresponding to thermal excitation of electrons from state 4 to state 5, $\tau_{54}$ is the lifetime corresponding to electron relaxation from state 5 to state 4, and $E_{54}$ is the energy difference between the two states. Thus, the key to suppressing carrier leakage is to increase the $E_{54}$ value as much as possible, while keeping the electrons injected in state 4 tightly confined, in order to keep them relatively cool\(^2\) (e.g., by using deep wells).\(^10\) With the DW design $E_{54}$ was increased from $\sim 46$ meV in conventional QCLs to $60$ meV.\(^1\) With a linear-taper TA design the $E_{54}$ value can be increased to $\sim 84$ meV (Fig. 1), and for the fabricated TA QCLs $E_{54}$ was increased to $77$ meV (Fig. 2).

In addition, the TA QCL design allows for increasing the upper-laser-state lifetime,\(^2\) compared to that of conventional QCLs, which, when coupled with complete suppression of carrier leakage, leads to threshold-current densities as much as $30\%$ lower than those of conventional QCLs of same geometry. Then, for an optimized TA QCL structure (i.e., $E_{54} \approx 100$ meV),\(^2\) by using our model\(^10\) for the maximum wallplug efficiency, $\eta_{wp,max}$, we estimate\(^2\) maximum, single-facet pulsed and CW RT $\eta_{wp,max}$ values of $\sim 29\%$ and $\sim 27\%$, respectively; thus, approaching theoretically predicted values at $\lambda \approx 4.7$ $\mu$m.\(^8,9\) Furthermore, since QCL degradation appears to be strongly related to the amount of device heating,\(^4\) significantly reducing the active-core temperature rise by suppressing carrier leakage in 2-D, conduction-band engineered QCLs is likely to lead to dramatically improved device reliability in CW operation.

The implementation of the deep-well TA concept to QCLs emitting at wavelengths $\leq 4.0$ $\mu$m, in order to significantly increase their CW wallplug efficiency as well as ensure long-term reliability, is possible by using growth on metamorphic-buffer-layer (MBL) virtual substrates,\(^11\) in order to maintain basically the same strain as for 4.5-5.0 $\mu$m-emitting QCLs. That will enable the development of a new class of QCLs holding the potential for significantly improved performance in the 3.0-4.0 $\mu$m wavelength range than currently possible.

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