Quantum cascade lasers (QCLs) are compact semiconductor light sources operating in the midinfrared spectral region (from ~3 to 20 μm) with high performance at room temperature. These devices are now commercially available and have a number of important military and civilian applications that broadly fall into two spectral bands, the mid- and longwave infrared (MWIR and LWIR), respectively. The MWIR applications are highlighted by technologies for protecting aircraft from shoulder-fired missiles. In the LWIR range, most applications are related to various sensing problems, such as gas sensing for toxic industrial chemicals and explosives, as well as laser detection and ranging, and free space optical communications. Many of these applications would benefit from improved QCL performance, specifically higher output power and better wallplug efficiency (WPE), defined as the ratio between optical output power and electrical power. Optical power exceeding 1 W and WPE of approximately 10% in continuous wave (cw) mode at room temperature has recently been reported for QCLs emitting at 4.6 μm.1–3 Higher optical power and WPE will lead to larger dynamic range, higher sensitivity, smaller size, and lower power requirements for systems incorporating these devices. Continued progress in this area strongly depends on how well different QCL structure designs allowing simultaneous optimization of several design parameters influencing laser performance. Following the growth, the structure was processed in buried heterostructure. Maximum single-ended continuous-wave optical power of 3 W was obtained at 293 K for devices with stripe dimensions of 5 mm×11.6 μm. Corresponding maximum wallplug efficiency and threshold current density were measured to be 12.7% and 0.86 kA/cm². © 2009 American Institute of Physics.

One way of increasing the structure design flexibility is to remove the two phonon resonance condition, i.e., \( E_{32} \) and \( E_{21} \) both simultaneously being equal to \( E_{1D} \) without sacrificing the efficient carrier extraction from the lower laser compared to the single-phonon resonance design.4,5 the two-phonon resonance design has the advantage of lowering carrier population in the lower laser level 3 due to reduced carrier thermal backfilling into this state from the lowest active region state 1.6 However, once the restrictive two-phonon condition is met, there is not much flexibility remaining for changing other parameters of the design since active region layers thicknesses are essentially fixed by the resonance condition and the desired laser transition energy. In particular, it is difficult to increase energy spacing \( E_{54} \) between the upper laser level 4 and the active region level 5 above it, a method to suppress parasitic carrier injection into the latter state, since level 5 is mostly localized in the same quantum wells as the low active region levels 2 and 1.

A strain-balanced, InP-based quantum cascade laser structure, designed for light emission at 4.6 μm using a new nonresonant extraction design approach, was grown by molecular beam epitaxy. Removal of the restrictive two-phonon resonant condition, currently used in most structure designs, allows simultaneous optimization of several design parameters influencing laser performance. Following the growth, the structure was processed in buried heterostructure. Maximum single-ended continuous-wave optical power of 3 W was obtained at 293 K for devices with stripe dimensions of 5 mm×11.6 μm. Corresponding maximum wallplug efficiency and threshold current density were measured to be 12.7% and 0.86 kA/cm². © 2009 American Institute of Physics.

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level. The carrier lifetime $\tau_i$ for an energy level $i$ can be written as

$$\frac{1}{\tau_i} = \sum_J \frac{1}{\tau_{ij}},$$

(1)

where $\tau_{ij}$ is the scattering time from the energy level $i$ to a final level $j$ and the summation is over all possible final states. Each carrier transition time $\tau_{ij}$ reaches its minimum when energy spacing $E_{ij}$ is equal to $E_{LO}$ and monotonically increases when $E_{ij}$ increases above $E_{LO}$. Equation (1) suggests that the energy spacing $E_{ij}$ can be increased substantially without increasing $\tau_i$ provided that there are at least two final levels $1$ and $1'$, instead of just one level $1$, for a transition from level 2. Significantly, carrier wave functions of these states, $1$ and $1'$, should have a large overlap with the wave function of the level 2. In this case, the summation over additional final states in Eq. (1), instead of just one, compensates for the increase in scattering times to individual final states due to increase in transition energies above $E_{LO}$, and leads to lifetimes of lower states comparable to those achieved in two-phonon design. We named this design approach nonresonant extraction, or NRE. In analogous manner, the energy spacing $E_{32}$ can also be substantially increased without increasing $\tau_i$ provided that there are at least two final states 2 and $2'$ for a transition from level 3. Removal of the two-phonon resonant condition makes the NRE approach a very attractive tool for QCL design. In this paper we present a description of a QCL structure designed using the NRE approach with corresponding record-high QCL experimental performance.

A conduction band diagram with the most relevant wave functions representing two gain stages of the structure is shown in Fig. 1. The active region of the structure is based on highly strained ($\sim 1\%$) $\text{In}_{0.67}\text{Ga}_{0.33}\text{As}$/\text{Al}_{0.64}\text{In}_{0.36}\text{As}$ quantum wells and barriers with strain compensation in each stage. Doping level was empirically adjusted so that roll over current density of the optical power vs. current characteristic stage. Doping level was empirically adjusted so that roll over quantum wells and barriers with strain compensation in each significantly above LO phonon energy. In addition, level 1 closely spaced with level 1. Second, the energy spacing be-

increases when $E_{ij}$ increases above $E_{LO}$. This suggests that the energy spacing $E_{ij}$ can be increased without increasing $\tau_i$, allowing us to use two final levels 1 and 1’, instead of just one level 1, for a transition from level 2. Consequently, carrier wave functions of these states, 1 and 1’, should have a large overlap with the wave function of the level 2. In this case, the summation over additional final states in Eq. (1), instead of just one, compensates for the increase in scattering times to individual final states due to increase in transition energies above $E_{LO}$, and leads to lifetimes of lower states comparable to those achieved in two-phonon design. We named this design approach nonresonant extraction, or NRE. In analogous manner, the energy spacing $E_{32}$ can also be substantially increased without increasing $\tau_i$ provided that there are at least two final states 2 and 2’ for a transition from level 3. Removal of the two-phonon resonant condition makes the NRE approach a very attractive tool for QCL design. In this paper we present a description of a QCL structure designed using the NRE approach with corresponding record-high QCL experimental performance.

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Preliminary experimental results for the structure described above, grown using metal organic chemical vapor deposition (MOCVD) and processed into buried heterostructure (BH) geometry using wet chemical etching, were reported in Ref. 1. In the present work, in addition to the description of the NRE concept and the band diagram of the structure, we also present new data, which show nearly a factor of 2 of improvement in optical power emitted by our QCLs, achieved using improved epigrowth and processing.

The QCL active region, along with the waveguide and contact layer sequence discussed in the previous work, was grown by molecular beam epitaxy (MBE).

Initially, part of the wafer was processed into round mesa devices for spectral electroluminescence characterization. Comparison between the electroluminescence spectra for MBE and MOCVD grown wafers is shown in Fig. 2. In addition to a slight blueshift of the peak, the MBE mesa demonstrated 20% reduction in linewidth (26.3 versus 32.7 meV), which has direct impact on laser performance. First, differential gain is inversely proportional to the linewidth.5 Another contribution comes from nonresonant intersubband transitions, which can have high matrix element and, as a consequence, can significantly contribute to overall losses through “tails” of Lorentzian distribution.8,9 If the detuning between the resonance and the laser transition significantly exceeds the linewidth, these nonresonant losses are directly proportional to the linewidth. Therefore, a larger linewidth simultaneously increases nonresonant intersubband losses and reduces peak gain, both leading to higher laser threshold current density. The 20% improvement in linewidth for MBE-material should not be interpreted as inherent advantage for this growth method. Instead, the comparison between MOCVD and MBE-grown structures should be interpreted as a comparison between two growth runs under different conditions with different linewidth.

The wafer was then processed into a BH geometry. First, a combination of reactive ion etching and wet chemical etching was used to form the ridges, which were then overgrown with semi-insulating iron-doped InP. Resultant BH profile is shown in the inset of Fig. 2. After conventional substrate thinning, polishing, and epide/substrate metallization steps, the epide was electroleptated with approximately 5 $\mu$m thick
lower nonresonant intersubband losses. Figure 3 shows a comparison between the pulsed and cw performance of a HR-coated 3 mm long laser. Threshold current density, slope efficiency, and maximum WPE in pulsed/cw mode after correction for the measurement setup wiring resistance equal to 0.26 Ohm (without correction) were measured to be 0.925/0.975 kW cm², 4.1/3.3 W/A, and 15.4/13.0% (15.1%/12.8%), respectively. 13% is the highest WPE reported for single-ended emission for QCLs. Single-ended output is desirable, since it allows straightforward systems integration. High performance QCLs with stripe width of 11.6 μm mounted on AlN was 11.5% at 2.93 K. In addition, the threshold current density and slope efficiency were measured to be 0.867 kW cm² and 3.3% respectively. Ratio of maximum power in pulsed to cw mode was found to be 1.53. Electromigration of indium solder used for laser bonding to the diamond submounts significantly reduces laser lifetime. Therefore, indium/diamond combination cannot be used in commercial applications. However, such results are of significant scientific and technical interest since diamond has the highest conductivity among all known materials, and therefore, the data show the upper limit for cw performance.

In conclusion, we presented a new QCL design approach based on nonresonant extraction that permitted us to achieve record-high continuous wave QCL performance at room temperature. We showed that this approach offers more design flexibility compared to the traditional two-phonon design. cw room temperature WPE of 13.0% and maximum power of 3 W for single-facette emission were measured for QCLs grown by MBE and processed into BH using reactive ion etching/wet etching combination.

This work was supported in part through a DARPA Contract No. W911QX-07-C-0041 (approved for public release, Distribution Unlimited). The work at Harvard University was performed in part at the Center for Nanoscale Systems, a member of the National Nanotechnology Infrastructure Network, which is supported by the National Science Foundation under NSF Award No. ECS-0335765.

FIG. 3. (Color online) cw and pulsed power vs current and voltage vs current characteristics measured at 293 K for a 3 mm long, HR-coated laser chip with stripe width of 9.5 μm mounted on AlN submount.

FIG. 4. (Color online) cw and pulsed power vs current and voltage vs current characteristics measured at 293 K for a 5 mm long, HR-coated laser chip with stripe width of 11.6 μm mounted on diamond submount.