# Type-I interband cascade lasers near 3.2 $\mu$m

Yuchao Jiang,[1] Lu Li,[1] Rui Q. Yang,[1,a)] James A. Gupta,[2] Geof C. Aers,[2]
Emmanuel Dupont,[2] Jean-Marc Baribeau,[2] Xiaohua Wu,[2] and Matthew B. Johnson[3]
[1]*School of Electrical and Computer Engineering, University of Oklahoma, Norman, Oklahoma 73019, USA*
[2]*National Research Council of Canada, Ottawa K1A 0R6, Canada*
[3]*Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, Oklahoma 73019, USA*

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Interband cascade (IC) lasers have been demonstrated based on type-I InGaAsSb/AlAsSb quantum well (QW) active regions. These type-I IC lasers are composed of 6-cascade stages and InAs/AlSb superlattice cladding layers. In contrast to the use of quinary AlGaInAsSb barriers for active region in previous type-I QW lasers, the type-I QW active region in each stage is sandwiched by digitally graded multiple InAs/AlSb QW electron injector and GaSb/AlSb QW hole injector. The fabricated type-I IC lasers were able to operate in continuous wave and pulsed modes at temperatures up to 306 and 365 K, respectively. The threshold current densities of broad-area lasers were around 300 A/cm$^2$ at 300 K with a lasing wavelength near 3.2 $\mu$m. The implications and prospects of these initial results are discussed. © *2015 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4907326]

Efficient mid-infrared (IR) semiconductor lasers are needed to meet the growing demands of many civilian and military applications. These applications for mid-IR wavelengths ($\lambda \geq 2.3\,\mu$m) include environmental and chemical-warfare monitoring, medical diagnostics, IR lidar, free-space communications, infrared countermeasures (IRCM), IR illumination, and gas sensing. Currently, research and development efforts mainly focus on three mid-IR semiconductor laser technologies: conventional type-I GaSb-based quantum well (QW) lasers,[1–3] intersubband quantum cascade (QC) lasers,[4–6] and interband cascade (IC) lasers.[7–14] With quinary AlGaInAsSb barriers, type-I GaSb-based QW lasers were able to achieve continuous wave (cw) operation at room temperature (RT) with lasing wavelengths up to about 3.4 $\mu$m,[1–3] while IC lasers based on type-II QW active regions can operate in cw mode at RT with low threshold current densities in a wide mid-IR wavelength spectrum from 3 to about 6 $\mu$m. Also, it is feasible to incorporate type-I QW active regions into IC laser structures.[8,15] As such, the combination of enhanced optical gain with a large wave-function overlap in a type-I QW and advantages of cascade structure (*e.g.*, uniform carrier injection and low parasitic loss due to series resistance[9]) would possibly lead to reduced threshold carrier concentration compared to type-II IC lasers. Consequently, free-carrier absorption loss and Auger recombination may also be reduced with a lowered threshold carrier concentration, resulting in improvements such as a further drop in threshold current density and increased output power.

Early experimental studies of type-I IC lasers were carried out in 1996–1998 using MOVPE-grown InAsSb/GaAsSb/AlAsSb structures[15,16] with lasing at low temperatures. Some later efforts were also attempted toward the development of type-I IC lasers.[17–19] Recently, cascaded type-I $Ga_{1-x}In_xAs_ySb_{1-y}$ QW diodes that lase in the cw mode at RT in a wavelength range from 2.4 to 3.2 $\mu$m have been demonstrated.[20–23] Although they are still in a preliminary stage of development, type-I IC lasers have already exhibited significantly higher differential quantum efficiencies and output powers (*e.g.*, 0.96 W near 3 $\mu$m with a lower threshold current[23]) than for non-cascade diode lasers, suggesting great potential for type-I IC lasers. The cascade diode lasers reported in Refs. 20–23 were formed essentially by connecting two or three conventional diode lasers via a type-II heterointerface, in which quinary AlGaInAsSb barrier layers were used. Here, we report the demonstration of type-I IC lasers without using quinary AlGaInAsSb barrier layers. These IC lasers were able to lase at wavelengths near 3.2 $\mu$m at temperatures up to 365 and 305 K in pulsed and cw modes, respectively, which is comparable to the reported operating temperatures of the state-of-art type-I GaSb-based lasers[1–3] and recently reported type-I IC lasers[22] at similar wavelengths.

The type-I IC laser structure was designed to have six cascade stages sandwiched by two 200-nm-thick GaSb separate confinement layers (SCLs) with two InAs/AlSb superlattice (SL) cladding structures on the top and the bottom of the SCLs. The calculated band profile (based on a two-band model[24,25]) and detailed layer sequence of one cascade stage is shown in Fig. 1, where the active QW layer is ~~$Ga_{0.55}In_{0.45}$~~ $As_{0.22}Sb_{0.78}$, the electron injector is composed of digitally graded 8 InAs/AlSb QWs, and the hole injector consists of 3 AlSb/GaSb QWs. The entire IC laser structure was grown on an *n*-type GaSb substrate in a V90 molecular beam epitaxy (MBE) system using As and Sb valved cracker cells and conventional group-III and dopant effusion cells. The InAs layers of the central 4 QWs in the electron injector of each cascade stage were doped with Si to $2.3 \times 10^{18}\,cm^{-3}$. Because of the compressive strain from the active QW layer (GaInAsSb), AlAs interfaces were used to achieve balanced strain in each cascade stage.

The initial wafer (V1046) was processed into deep-etched broad-area (150- and 100-$\mu$m-wide) mesa stripe and narrow-ridge (10-, 12-, 15-, 20-$\mu$m-wide) lasers by contact photolithography and wet chemical etching. The processed wafer was cleaved into laser bars with lengths from 1.5 to 2.0 mm and the facets were left uncoated. The laser bars

a)Also with Applied Quantum Enovation, E-mail: Rui.Q.Yang@ou.edu

 

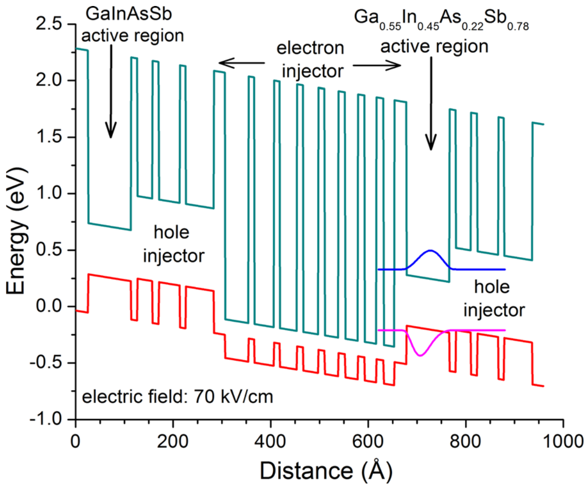


FIG. 1. Calculated band profile of one cascade stage under an electric field of 70 kV/cm and the layer sequence.

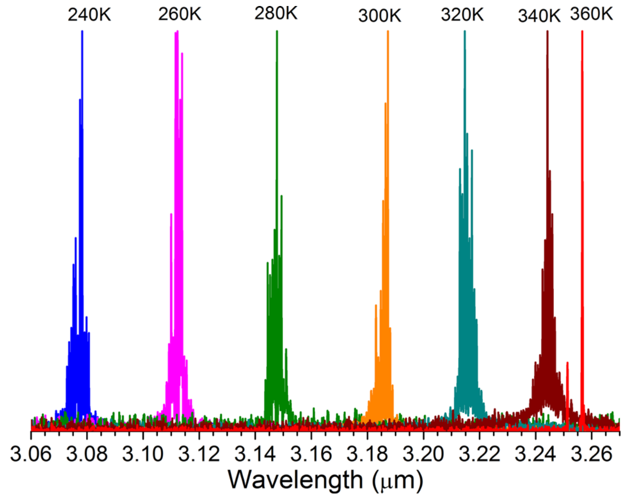


FIG. 3. Pulsed lasing spectra near the threshold (360 K spectrum from a 100-$\mu$m-wide device, the rest from a 150-$\mu$m-wide device).

were mounted epilayer side up on copper heat sinks with indium solder and placed on the cold finger of a cryostat for measurements in cw and pulsed modes. In pulsed measurements, the applied current pulse width was 1 $\mu$s at a repetition rate of 5 kHz.

Broad-area devices could lase in cw mode at heat sink temperature ($T$) up to $\sim$250 K at a wavelength of 3.15 $\mu$m as shown in Fig. 2. Current-Voltage-Light ($I$-$V$-$L$) characteristics are also shown in Fig. 2 for a 150-$\mu$m-wide device in cw operation. At 80 K, the lasing wavelength was 2.81 $\mu$m with a threshold voltage of 3.66 V and threshold current density of 4.3 A/cm$^2$, and the cw output power was $\sim$120 mW/facet at a current of 200 mA with a slope of 0.63 W/A. This implied an external quantum efficiency of 2.86 and confirmed the efficient cascade action. The actual output power and external quantum efficiency may be somewhat higher than the above reported values because the measurement system calibration included corrections for the window transmission loss without accounting for beam divergence. In pulsed conditions, these broad-area devices could lase at temperatures up to 360 K with a lasing wavelength near 3.25 $\mu$m as shown in Fig. 3. The lasing wavelength red shifted with the heat-sink temperature at a rate of 1.8 nm/K from $\sim$3.08 $\mu$m at 240 K. At 300 K, the threshold current density was as low as 310 A/cm$^2$ with a threshold voltage of $\sim$3.5 V. This translates to a threshold input power density of below 1.1 kW/cm$^2$, which would allow cw operation of narrow-ridge devices at RT. Broad-area devices made from the second MBE grown wafer (V1050) of this type-I IC laser structure exhibited a somewhat lower threshold current density (*e.g.*, at 300 K, 295 A/cm$^2$ with a threshold voltage of $\sim$3.4 V at a lasing wavelength of 3.13 $\mu$m). The temperature dependences of threshold current densities are shown in Fig. 4 for representative devices. The characteristic temperature $T_0$ was 47 and 50 K in the pulsed operation up to about 300 K for broad-area devices made from the initial wafer and the second wafer, respectively. The threshold current density increased relatively quickly at temperatures higher than 300 K due to Joule heating with larger current injection into broad-area devices even under pulsed operation. Around RT, the threshold current density is higher than the reported value ($\sim$100 A/cm$^2$ at 290 K) for recent type-I IC lasers with quinary barriers with a lasing wavelength slightly shorter than 3 $\mu$m,[20,23] but lower than the value ($\sim$700 A/cm$^2$ at 290 K)

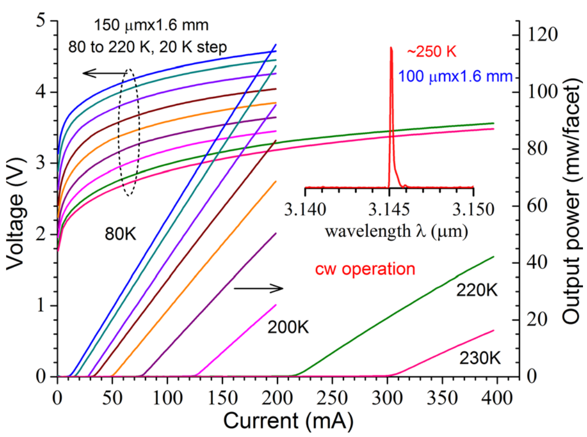


FIG. 2. Current-voltage-light characteristics for a 150-$\mu$m-wide device in cw operation. The inset is cw lasing spectrum from a 100-$\mu$m-wide device at a heat-sink temperature of $\sim$250 K.

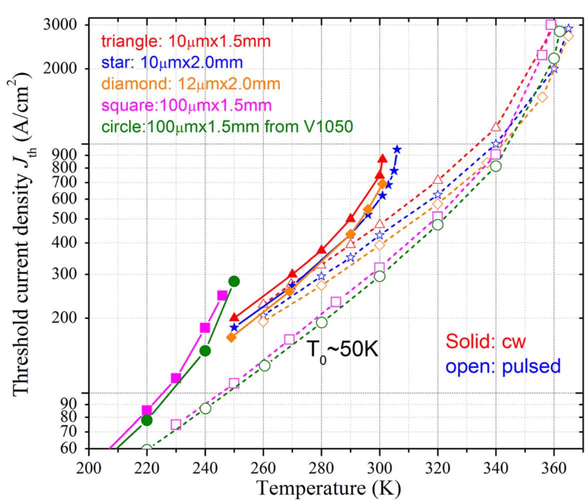


FIG. 4. Threshold current density vs heat-sink temperature for both broad-area and narrow-ridge lasers made from wafers V1046 and V1050 (one specified).

for the two-stage type-I IC laser with a similar lasing wavelength (~3.15 $\mu$m).[22] This is because the threshold current density in type-I QW lasers is very sensitive to the increase of the lasing wavelength related to the finite valence band offset and these lasers have not been optimized. Ideally, the threshold current density should scale inversely with the increase of the number of cascade stages. However, this ideal inverse relationship may not occur in practice. As reported in Ref. 23, the threshold current density of the three-stage type-I IC laser was not lower than that of the two-stage laser. Hence at this time, it is unclear how the threshold current density is affected by the number of cascade stages for these type-I IC lasers. This relationship will be a subject of the further study. Nevertheless, the approach described here using InAs/AlSb(As) electron injectors and GaSb/AlSb(As) hole injectors without being limited by quinary AlGaInAsSb barriers can increase the valence band offset and thus improve type-I interband lasers at the longer wavelengths, especially once they are optimized.

Narrow-ridge devices with about 4-$\mu$m-thick electroplated gold layer on the top were able to lase in cw mode at temperatures up to 306 K at 3.23 $\mu$m as shown in Fig. 5. This maximum cw operating temperature is comparable to (or slightly higher than) the recently reported type-I IC lasers[22] at similar wavelengths. The cw *I-V-L* characteristics of a 10-$\mu$m-wide and 2-mm-long device at several heat-sink temperatures are also shown in Fig. 5. The Joule heating in the laser was substantial at 300 K as reflected by the thermal rollover in Fig. 5. Nevertheless, the detected output power exceeded 2 mW/facet at 300 K without accounting for beam divergence loss. The input power at threshold was slightly less than 0.46 W at 300 K, which is higher than the state-of-art type-II IC lasers,[12] but encouraging considering that this was from the initial attempt. The cw operation of these type-I IC lasers was affected by their relatively high thermal resistance. For example, the specific thermal resistance for a 10-$\mu$m-wide ridge laser was 8 K cm$^2$/kW, which is higher than the reported value (5.4 K cm$^2$/kW) for a 12-stage 10-$\mu$m-wide ridge type-II IC laser with a similar layer structure and SL cladding layers.[26] The higher thermal resistance is mainly attributed to imperfect chip mounting and the thinner top gold layer (4 vs. 7 $\mu$m). Consequently, the cw operating temperature and output power were limited because the maximum allowable cw threshold current density and output power are inversely proportional to the thermal resistance. These properties can be significantly improved with facet coatings and better thermal management such as epilayer-down mounting and reduced ridge width as employed in recently reported type-II and type-I IC lasers.[12,20–23]

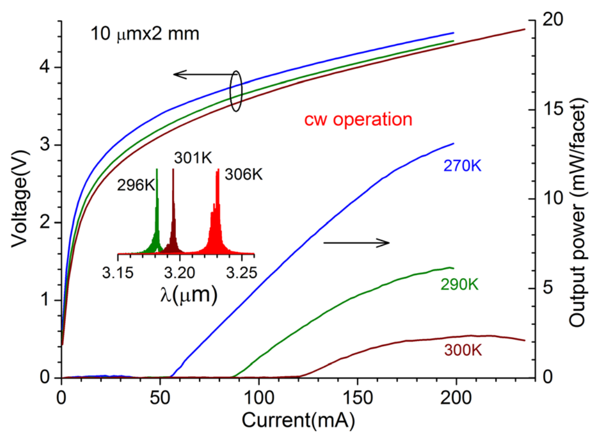


FIG. 5. Current-voltage-light characteristics for a 10-$\mu$m-wide device in cw operation. The inset is its cw lasing spectrum at a heat-sink temperature of ~296–306 K.

In pulsed mode, these narrow-ridge devices could lase at temperatures up to 365 K near 3.26 $\mu$m with much less Joule heating compared to broad-area lasers. Their threshold current densities were generally higher than corresponding values of broad-area lasers at temperatures below 340 K as shown in Fig. 4. The difference between them was more evident at lower temperatures. For example, at 300 K, the pulsed threshold current density in a 10-$\mu$m-wide narrow-ridge device was about 50% higher than that in a broad-area laser at the same cavity length, which is substantial in contrast to ~21% higher reported for type-II IC lasers.[27] This suggests somewhat significant current leakage from side walls with imperfect passivation, which contributed to a higher $T_0$ (~57 K) for narrow-ridge devices compared to broad-area devices. By comparing the threshold current densities of narrow-ridge devices with different cavities, the internal loss was estimated to be about 12 cm$^{-1}$ at 300 K, which is similar to the recently reported two-stage type-I IC lasers at this wavelength,[22] but higher than the lowest value (~5 cm$^{-1}$) reported for type-II IC lasers.[12] These imply further room for type-I IC lasers to lower the internal loss and reduce the surface leakage to achieve better performance.

In summary, type-I IC lasers were demonstrated with both pulsed and cw operation above RT with the use of SL cladding layers and without using quinary AlGaInAsSb barrier layers. This demonstration showed an alternative way to achieving efficient semiconductor mid-IR lasers. However, although these initial results are encouraging, type-I IC lasers are still in a very preliminary phase. Many aspects of type-I IC lasers have not been explored and they are far from optimized. Extensive investigations in different directions and with different designs are required to achieve the full potential of type-I IC lasers.

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[1]G. Belenky, L. Shterengas, M. V. Kisin, and T. Hosoda, "Gallium antimonide (GaSb)-based type-I quantum well diode lasers: recent development and prospects," in *Semiconductor Lasers: Fundamentals and Applications*, edited by A. Baranov and E. Tournie (Woodhead Publishing Limited, Cambridge, UK, 2013), Chap. 11.

[2]K. Vizbaras, A. Vizbaras, A. Andrejew, C. Grasse, S. Sprengel, and M.-C. Amann, "Room-temperature type-I GaSb-based lasers in the 3.0–3.7 $\mu$m wavelength range," Proc. SPIE **8277**, 82771B (2012); and references therein.

[3]J. A. Gupta, A. Bezinger, P. J. Barrios, J. Lapointe, D. Poitras, and P. Waldron, "High-resolution methane spectroscopy using InGaAsSb/AlInGaAsSb laterally coupled index-grating distributed feedback laser diode at 3.23 $\mu$m," Electron. Lett. **48**, 396 (2012).

[4]J. Faist, F. Capasso, D. L. Sivco, C. Sirtori, A. L. Hutchinson, and A. Y. Cho, "Quantum cascade laser," Science **264**, 553 (1994).

[5]C. K. N. Patel, "High Power Infrared QCLs: Advances and Applications," Proc. SPIE **8268**, 826802 (2012); and references therein.

[6]N. Bandyopadhyay, S. Slivken, Y. Bai, and M. Razeghi, "High power, continuous wave, room temperature operation of $\lambda \sim 3.4\,\mu$m and $\lambda \sim 3.55\,\mu$m InP-based quantum cascade lasers," Appl. Phys. Lett. **100**, 212104 (2012); and references therein.
[7]R. Q. Yang, "Infrared laser based on intersubband transitions in quantum wells," Superlattices Microstruct. **17**, 77 (1995).
[8]J. R. Meyer, I. Vurgaftman, R. Q. Yang, and L. R. Ram-Mohan, "Type-II and type-I interband cascade lasers," Electron. Lett. **32**, 45 (1996).
[9]R. Q. Yang and S. S. Pei, "Novel type-II quantum cascade lasers," J. Appl. Phys. **79**, 8197 (1996).
[10]R. Q. Yang, "Interband Cascade (IC) Lasers," in *Semiconductor Lasers: Fundamentals and Applications*, edited by A. Baranov and E. Tournie (Woodhead Publishing Limited, Cambridge, UK, 2013), Chap. 12; and references therein.
[11]I. Vurgaftman, W. W. Bewley, C. L. Canedy, C. S. Kim, M. Kim, C. D. Merritt, J. Abell, J. R. Lindle, and J. R. Meyer, "Rebalancing of internally generated carriers for mid-infrared interband cascade lasers with very low power consumption," Nat. Commun. **2**, 585 (2011).
[12]I. Vurgaftman, W. W. Bewley, C. L. Canedy, C. S. Kim, M. Kim, C. D. Merritt, J. Abell, and J. R. Meyer, "Interband cascade lasers with low threshold powers and high output powers," IEEE J. Sel. Top. Quantum Electron. **19**, 1200210 (2013); and references therein.
[13]R. Weih, M. Kamp, and S. Hofling, "Interband cascade lasers with room temperature threshold current densities below 100 A/cm$^2$," Appl. Phys. Lett. **102**, 231123 (2013).
[14]C. L. Canedy, J. Abell, C. D. Merritt, W. W. Bewley, C. S. Kim, M. Kim, I. Vurgaftman, and J. R. Meyer, "Pulsed and CW performance of 7-stage interband cascade lasers," Opt. Express **22**, 7702 (2014).
[15]A. A. Allerman, R. M. Biefeld, and S. R. Kurtz, "InAsSb-based mid-infrared lasers (3.8–3.9 $\mu$m) and light-emitting diodes with AlAsSb claddings and semimetal electron injection, grown by metalorganic chemical vapor deposition," Appl. Phys. Lett. **69**, 465 (1996).
[16]S. R. Kurtz, A. A. Allerman, R. M. Biefeld, and K. C. Baucom, "High slope efficiency, 'cascaded' midinfrared lasers with type I InAsSb quantum wells," Appl. Phys. Lett. **72**, 2093 (1998).
[17]R. Q. Yang and Y. Qiu, laser research at Jet Propulsion Laboratory from 2002 to 2004 (unpublished).
[18]J. R. Meyer, private communication about NRL unpublished results several years ago (2014).
[19]R. Q. Yang, M. B. Santos, and M. B. Johnson, "Interband cascade lasers based on type-I quantum well active regions," a proposal submitted to National Science Foundation in 2013 (unpublished).
[20]L. Shterengas, R. Liang, G. Kipshidze, T. Hosoda, S. Suchalkin, and G. Belenky, "Type-I quantum well cascade diode lasers emitting near 3 $\mu$m," Appl. Phys. Lett. **103**, 121108 (2013).
[21]L. Shterengas, R. Liang, G. Kipshidze, T. Hosoda, S. Suchalkin, and G. Belenky, "Cascade pumping of GaSb-based type-I quantum well diode lasers," Proc. SPIE **9002**, 900213 (2014).
[22]R. Liang, L. Shterengas, T. Hosoda, A. Stein, M. Lu, G. Kipshidze, and G. Belenky, "Diffraction limited 3.15 $\mu$m cascade diode lasers," Semicond. Sci. Technol. **29**, 115016 (2014).
[23]L. Shterengas, R. Liang, G. Kipshidze, T. Hosoda, G. Belenky, S. S. Bowman, and R. L. Tober, "Cascade type-I quantum well diode lasers emitting 960 mW near 3 $\mu$m," Appl. Phys. Lett. **105**, 161112 (2014).
[24]R. Q. Yang and J. M. Xu, "Analysis of transmission in polytype interband tunneling heterostructures," J. Appl. Phys. **72**, 4714 (1992).
[25]R. Q. Yang and J. M. Xu, "Bound and quasibound states in leaky quantum wells," Phys. Rev. B **46**, 6969 (1992).
[26]K. Mansour, Y. Qiu, C. J. Hill, A. Soibel, and R. Q. Yang, "Mid-IR interband cascade lasers at thermoelectric cooler temperatures," Electron. Lett. **42**, 1034 (2006).
[27]W. W. Bewley, C. L. Canedy, C. S. Kim, M. Kim, J. R. Lindle, J. Abell, I. Vurgaftman, and J. R. Meyer, "Ridge-width dependence of midinfrared interband cascade laser characteristics," Opt. Eng. **49**, 111116 (2010).