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Demonstration of a Quick Process to Achieve Buried Heterostructure QCL Leading to High Power and Wall Plug Efficiency

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ABSTRACT.

Together with the optimal basic design, buried heterostructure quantum cascade laser (BH-QCL) with semi-insulating regrowth offers unique possibility to achieve an effective thermal dissipation and lateral single mode. We demonstrate here for the first time realization of BH- QCLs with a *single step regrowth* of highly resistive (>1x10^8 ohm·cm) semi-insulating InP:Fe *in less than 45 minutes* in a flexible hydride vapour phase epitaxy process for burying ridges etched down to 10-15 µm deep both with and without mask overhang. The fabricated BH-QCLs emitting at ~4.7 µm and ~5.5 µm were characterized. 2 mm long 5.5 µm lasers with ridge width 17-22 µm, regrown with mask overhang, exhibited no leakage current. Large width and high doping in the structure did not permit high current density for CW operation. 5 mm long 4.7 µm BH-QCLs of ridge widths varying from 6-14 µm regrown *without* mask overhang, besides being spatially monomode, TM_{00}, exhibited WPE of ~8-9% with an output power of 1.5 – 2.5 W at room temperature and under CW operation. Thus, we demonstrate a simple, flexible, quick, stable and single-step regrowth process with extremely good planarization for realizing buried QCLs leading to monomode, high power and high WPE.

Keywords: Buried heterostructure quantum cascade lasers, high power QCL, High WPE QCL, HVPE regrowth.

1 INTRODUCTION

Quantum cascade laser (QCL) emerging from the physical concepts on the possibility of the amplification of electromagnetic waves in a semiconductor with a superlattice[1] was first demonstrated by Faist and co-workers[2]. It is now demonstrated to cover a wide range of spectrum from near-infrared to mid THz [3-4]. In virtue of such a wide coverage of wavelengths, QCLs have become attractive sources for spectroscopy, medical and biosensing, remote gas sensing, free-space communication and applications in defense security countermeasures. Several of these application areas necessitate high power, good beam quality, efficient thermal dissipation and high wall plug efficiency (WPE). Together with the optimal basic design, buried heterostructure QCL (BH-QCL) with semi-insulating regrowth offers unique possibility to achieve an effective thermal dissipation and lateral single mode which help to achieve the above expected performance. The first BH-QCL was realized by Beck et al. using unintentionally doped InP[5] by molecular beam epitaxy (MBE). Later, several investigators have demonstrated BH-QCLs by metal organic vapour phase epitaxy (MOVPE)[6,7,8] and gas source MBE[9,10]using semi-insulating Fe doped InP (SI-InP:Fe), which is already an established method in the fabrication of telecom lasers. So far hydride vapour phase epitaxy (HVPE) has not been used to fabricate BH-QCLs using SI-InP:Fe.

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This being an equilibrium process, its growth rate is one order of magnitude higher than that of the non-equilibrium processes such as MOVPE and MBE. In addition, its planarizing capacity, total selectivity during the growth on patterned (planar or non-planar) surfaces, non-appearance of "rabbit ears" near the ridge (or mesa) edge, flexibility in growing around [110] and [-110] oriented ridges, both with or without mask overhang, and insensitivity to the profile of the etched ridge are its unique features[11]. An added and attractive feature of an equilibrium process is the capability of conducting in-situ ridge etching and immediate regrowth, which has been demonstrated for telecom lasers[12]. The combination of ex-situ and in-situ etching and immediate regrowth for BH-vertical cavity surface emitting lasers with GaAs/AlAs Bragg mirrors has also been demonstrated[13]. This is particularly interesting for QCLs since the active layer contains Al containing layers, which when etched (as ridge) and exposed to atmosphere prior to regrowth, the risk of immediate oxidation can cause problems for regrowth. All these are attractive especially for the realisation of BH-QCLs lasers in short time. Maintenance of the QCL ridges at the regrowth temperatures for longer time to realize BH-QCL can cause severe inter well-barrier mixing as demonstrated with telecom lasers[14] leading to the loss of the originally designed laser characteristics. Hetero-cascade[15-16] and multi-stack QCLs[17-18], with several different active regions stacked on top of each other, are used to obtain a broad composite gain or increase peak power output. Such structures have thick etch ridges which puts severe demand in carrying out regrowth around very deeply etched (> 10 µm) ridges in short time. In addition, in future, advanced photonic integration with QCLs with arrayed waveguide gratings and detectors will be emerging and we foresee that HVPE is very useful as it has been demonstrated vital in the realisation of photonic integrated chip[19-20]. As QCLs have reached the commercialisation stage, it is imperative that the fabrication processes are also less time consuming, flexible and cost-effective. In this article we demonstrate for the first time realisation of BH-QCL by HVPE. We focus mainly on the regrowth aspects revealing its rapidity and flexibility in achieving well planarized BH-QCL. Chips characterized with unoptimised mounting exhibit an output power 1.5-2.5 W under continuous wave operation and at room temperature with a WPE of 8-9%.

2 EXPERMENTAL

Two basic sets of quantum cascade lasers were taken into consideration. The first set emitting at 5.5 µm with a bound-to-continuum design reproduced from Blaser et al.[21] was primarily meant to test the regrowth feasibility in terms of planarization with wet-etched ridges with overhang. The ridges were defined by photolithography using a 500 nm-thick SiO_2 hard mask, opened using a CF_4/Ar plasma etch. The ridges themselves were etched in a solution of HBr:HCl:H_2O_2:H2O = 20:10:2:100. For an etch depth of 8-9 microns, the expected undercut is ~3 µm on each side. After processing, these lasers were mounted epi-up and characterized. The 2 mm long chips contained ridges with a width ranging from 17-22 µm.

The second set contained lasers emitting at 4.7 µm. The structure of the laser is as described in[22]. These were processed so as to analyze the advantage of BH design in terms of thermal dissipation. Identical lasers were processed in two configurations, one in ridge-only variation where the ridges were covered with SiO_2 and the other with BH variation involving semi-insulating regrowth. These are shown schematically in Figure 1.

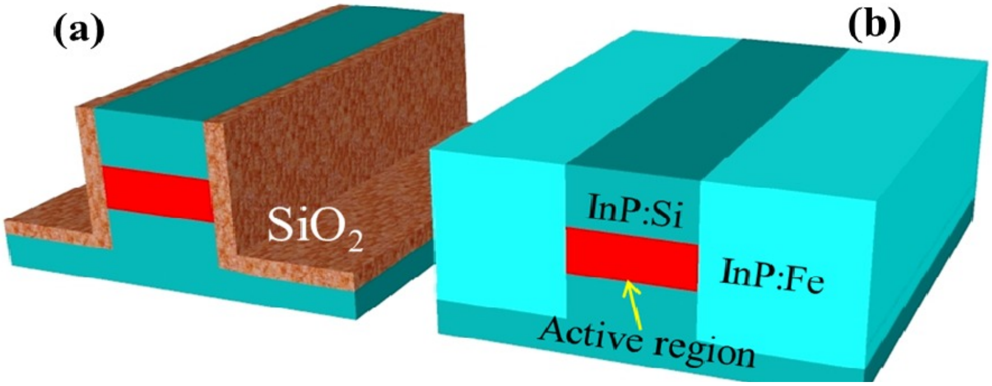

Figure 1. Schematic description of (a) ridge-only and BH b) QCLs from the second batch.

The ridges of width 4-14 µm were etched with inductively coupled plasma (ICP) etching using SiO_2 as the mask.. Ridge-only variation was further processed with a coating of SiO_2 as shown in Figure 1(a). BH was realized in a low pressure HVPE reactor with semi-insulating InP:Fe regrowth at a growth temperature of 600 ^{o}C. The reactor pressure was maintained at 20 mbar and total gas flow in the reactor was 900 sccm. The V to III ratio, $[PH_3]$/ [InCl] was 10. The growth time was adjusted depending on the etched ridge depth, < 45 minutes in all experiments. The processed lasers were cleaved, HR coated and characterized. HR coating is done by ion assisted deposition in a DENTON facility of SiO_2 followed by Ti/Au layer which provides the optical feedback. Standard characterization is made on a temperature stabilized bench with a peltier cooler. The mounting was done eip-side down on AlN submount using gold tin soldering. The second contact is taken from the rear facet since the substrate is conductive and wire bonded.

3 RESULTS AND DISCUSSIONS

3.1 5.5 µm QCL

In case of the first set of samples regrowth of InP:Fe was conducted on wet-etched ridge of 9 µm deep and mask overhang of ~3 µm on each side. A complete planarization obtained only in 13 minutes of regrowth time. The regrowth profile is shown in Figure 2.

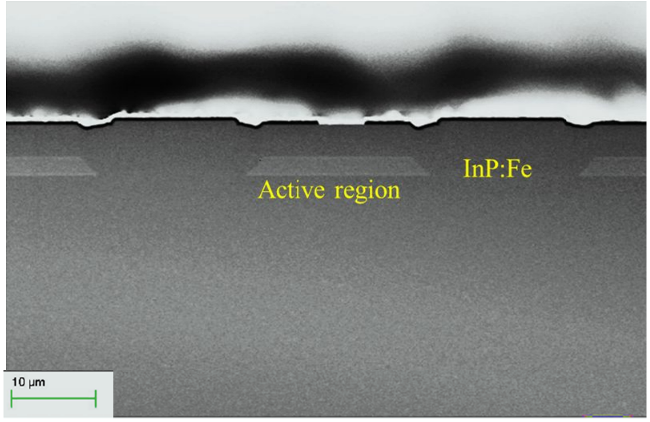

Figure 2: Cross-section SEM image of InP:Fe regrown 9 µm deep wet-etched ridge for 13 minutes

We observe that the regrown interface is seamless and the planarizing capacity is remarkable. The I-V curves measured under pulsed conditions with a duty cycle up to 20% indicate that there is no leakage. The reason why continuous wave operation is not reached may be attributed to the too large width of the ridges as well as large doping in the structure as can be inferred from the maximum current density of 4 kA/cm^2.

3.2 4.7 µm QCL

The cross-sectional view of the BH-QCL fabricated from a 8 µm deep etched ridge is shown in Figure 3. We also conducted in a separate experiment regrowth around µ-striped QCL[23] (not treated here). It is clearly seen that our regrowth process yields the most desirable planarization without any rabbit ear formation. The regrown interface is also clean. As we have conducted numerous experiments with varying depths of etched ridges, it is possible to summarize the InP:Fe regrowth time as a function of etched ridge depth, as in Figure 5.

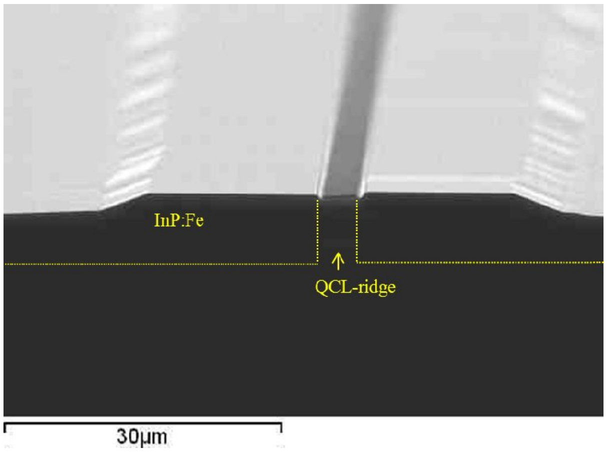

Figure 3. BH-QCL resulting from a 8 µm deep etched ridge

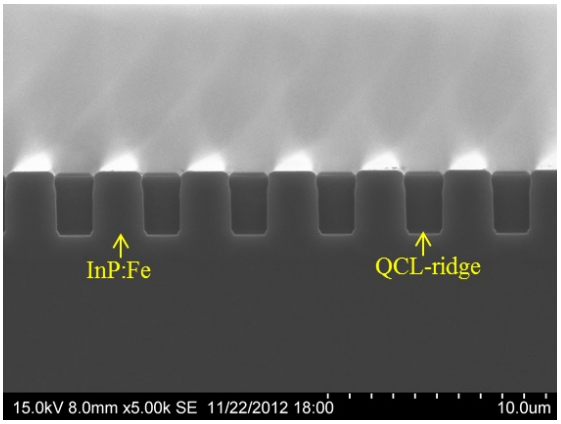

Figure 4. BH µ-striped QCL

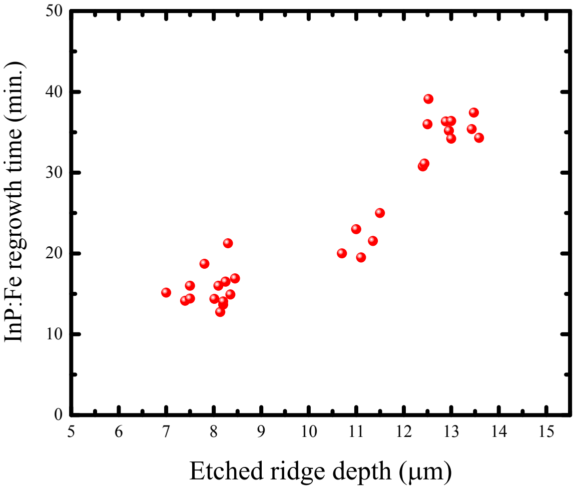

Figure 5 InP:Fe regrowth time depending upon the etched QCL ridge depth.

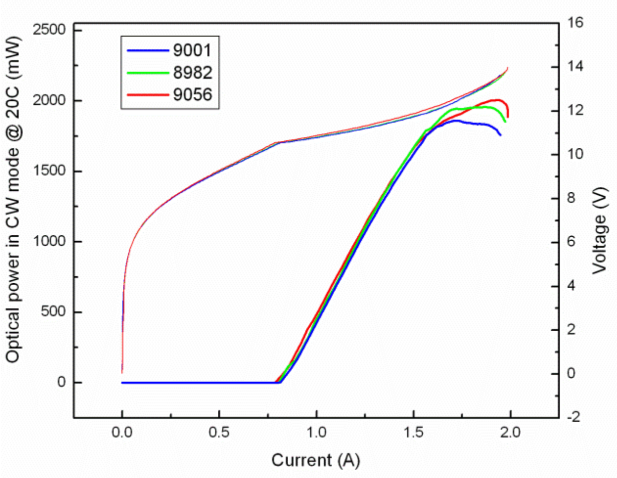

Figure 6 I-V-L curves under CW operation at RT of three 4.7 µm BH-QCLs of ridge with 10 µm. The etched depth was 6.5 µm

It is clear from this figure that the regrowth of InP:Fe around a 14 µm deep ridge can be done in less than 40 minutes. This quick regrowth time is particularly interesting to minimize the risk for the unwanted intermixing of well and barrier as described earlier[14]. The I-V-L curves for three BH-QCLs resulting from 10 µm wide and 6.5 µm deep ridge are shown in Figure. 6. The figure shows reproducible behaviour from laser to laser. Figure.7 depicts the far filed pattern of three lasers of 6, 12 and 14 µm ridge width and operating in a continuous wave at room temperature with 1.5, 2 and 2.1 A current levels, respectively. The far field pattern for all lasers maintain a single Gaussian line profile indicating spatially mono mode (TM00) behaviour.

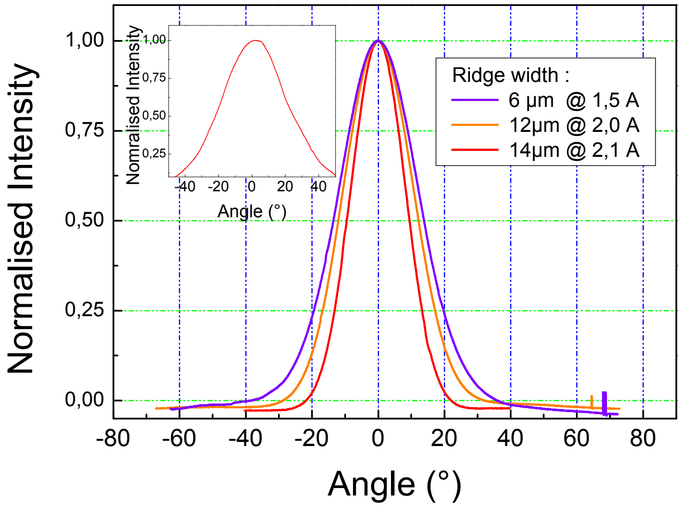

Figure 7 Far field pattern of the buried lasers with different ridge widths of 6-14 µm showing TM_{00} behaviour

We also analysed the maximum output power and WPE for all the lasers characterized and are summarized in Table 1.

Table 1 Summary of the BH-QCL performance in terms of maximum output power and WPE for varying ridge widths

Ridge Width (µm)	**Maximum output power under CW operation at RT (mW)**	**Maximum WPE (%)**
4	725	5.3
6	1 475	8.7
8	1 500	8.5
10	2 000	8.4
12	2 400	8.8
14	2 400	7.6

All the characterized lasers were 5 mm long and HR-coated. High values of output power and WPE for the lasers with unoptimised mounting suggests that the heat dissipation is very well facilitated due to the realization of BH configuration. Finally we compare the BH-QCLs (Figure 1(a) with ridge-alone QCLs (Figure1(b) in terms of maximum output power at 10^{o}C for different ridge widths. The results are shown in Figure 8.

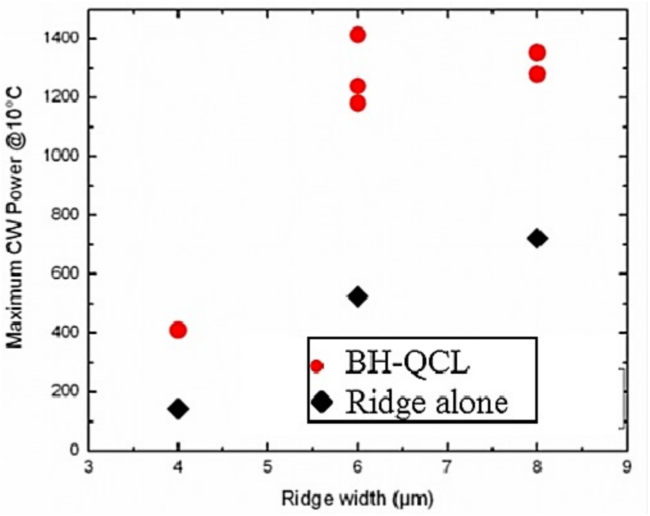

Figure 8. Comparison of maximum output power for BH-QCL (as cleaved) and ridge-alone QCL (HR-coated).

It is to be pointed out that the ridge-alone QCLs were HR-coated but not BH-QCLs. In spite of that, the BH-QCLs exhibit more than twice as much power as the ridge-alone QCL. It is known that thermal dissipation is anisotropic in the QCLs and the in-plane versus cross-plane ratio is typically around 2.5; higher in-plane conductivity is explained to be due to bulk-like dispersion of phonons whereas cross-plane dissipation is more complex in terms of phonon dispersion and can suffer largely from phonon reflections at the interfaces[24-25]. It can even be expected that the lateral heat dissipation in a buried heterostructure can get reduced if the regrown interface is not seamless as it might also involve certain amount of phonon scattering. Thus we have demonstrated that BH-QCL with a clean regrown interface is an effective way of gaining the thermal benefits.

3 CONCLUSIONS

In this study we demonstrated a quick process to achieve buried heterostructure QCL leading to high power and wall plug efficiency. For this we employed hydride vapour phase epitaxy. With a *single step regrowth* of highly resistive ($>1\times10^8$ ohm·cm) semi-insulating InP:Fe *in less than 45 minutes,* BH-QCLs can be realized with burying ridges etched down to 10-15 µm deep. In addition, it has been shown that the current process is largely insensitive to ridge profile, mask overhang and does not lead to rabbit-ear growth near the ridge. The HR-coated lasers emitting at ~5.5 and 4.7 µm were characterized. The ridge width was very large in the former case and hence these were subjected to only pulsed operation. Both of them showed no leakage even at high currents. The latter were analysed in depth with CW operation. Very reproducible results were obtained on the 5 mm long lasers of ridge widths varying from 4-14 µm. Besides being spatially monomode, TM_{00} all the characterized lasers exhibited WPE of ~8-9% with an output power of 1.5 – 2.5 W at room temperature and under CW operation. The performance can be further improved by proper mounting and facet coating. BH-QCLs were also compared with the ridge-alone QCLs and the former outperform the latter in their output power even though the latter were HR-coated and the former were only as-cleaved. Thus, HVPE process is extremely suitable for mass production of high performance QCLs.

Acknowledgments

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REFERENCES

[1] R.F. Kazarinov and R.A. Suris, “Possibility of the amplification of electromagnetic waves in a semiconductor with a superlattice,” *Sov. Phys. Seicond.*, **5**, 207 (1971).

[2] J. Faist, F. Capasso, D.L.Sivco, C. Sirtori, A.L.Hutchinson, A.Y.Cho, “Quantum Cascade Laser,” *Science*, **264**, 553 (1994).

[3] O. Cathabard, R. Teisier, J. Devenson, J.C. Moreno, A.N. Baranov, “Quantum cascade lasers emitting near 2.6μm,” Appl. Phys. Lett., **96**, 141110 (2010).

[4] C. Walther, M. Fischer, G. Scalari, R. Terazzi, N. Hoyler, J. Faist, “Quantum cascade lasers operating from 1.2 to 1.6 THz,” Appl. Phys. Lett., 91, 131322 (2007).

[5] M. Beck, J. Faist, C. Gmachl, F. Capasso, D.L. Sivco, J.N. Baillargeon and A.Y. Cho, “Buried heterostructure quantum cascade lasers,” SPIE **3284**, 231-236 (1998).

[6] F.Xie, C.G.Caneau, H.P.LeBlanc, N.J.Visovsky, S.Coleman, L.C.Hughes, C.Zah, “High-temperature continuous-wave operation of low power consumption single-mode distributed-feedback quantum-cascade lasers at λ~5.2μm,” *Appl.Phys.Lett.*, **95**, 091110 (2009).

[7] Y. Bai, S. Slivken, S. Kuboya, S.R. Darvish, M. Razeghi, “Quantum cascade lasers that emit more light than heat,” *Nat. Photonics*. **4,** 99–102 (2010).

[8] L. Diehl, D. Bour, S. Corzine, J. Zhu, G. Höfler, M. Lončar, M. Troccoli, and, F. Capasso, “High-temperature continuous wave operation of strain-balanced quantum cascade lasers grown by metal organic vapor-phase epitaxy,” *Appl. Phys. Lett*. **89** 081101 (2006).

[9] M. Chashnikova, G. Monastyrskyi, A. Aleksandrova, M. Klinkmüller, M.P. Semtsiv, W.T. Masselink, “Buried-heterostructure quantum-cascade laser overgrowth by gas-source molecular beam-epitaxy,” *Appl. Phys. Lett.,* **100**, 213504 (2012).

[10] M.P. Semtsiv, A. Aleksandrova, M. Elagin, G. Monastyrskyi, J.-F. Kischkat, Y.V. Flores, W.T. Masselink, “Semi-insulating InP:Fe for buried-heterostructure strain-compensated quantum-cascade lasers grown by gas-source molecular-beam epitaxy,” *J. Cryst. Growth*. **378,** 125–128 (2013).

[11] S. Lourdudoss and O.Kjebon, “Hydride Vapour Phase Epitaxy Revisited,” *IEEE Journal of Selected Topics in Quantum Electronics*, **3(3),** 749-767 (1997).

[12] E. Rodríguez Messmer, T.Lindström, S.Lourdudoss, “In-situ mesa etching and immediate regrowth in a hydride vapour phase epitaxy reactor for buried heterostructure fabrication*,” J. Crystal Growth*, **210**, 600-612 (2000).

[13] C. Angulo Barrios, E. Rodriguez Messmer, M. Holmgren, A. Risberg, J. Halonen, and S. Lourdudoss, “Epitaxially regrown GaAs/AlGaAs laser mesas with semi-insulating GaInP:Fe and GaAs:Fe,” *Journal of Electronic Materials,* **30(8)**, 987-991 (2001).

[14] W.Glew, J.P.Stagg, P.D.Greene, A.T.R.Briggs, S.Bradshaw, and J.H.Marsh, “Thermal instability of InGaAs/InGaAsP quantumwells,”in *3rd Int. Conf. Indium Phosphide and Related Materials*, Cardiff, U.K., 1991, 515–518.

[15] C. Gmachl, D. L. Sivco, J. N. Baillargeon, A. L. Hutchinson, F. Capasso, and A. Y. Cho, “Quantum cascade lasers with a heterogeneous cascade: Two-wavelength operation,” *Appl. Phys. Lett.,* **79**, 572-574 (2001).

[16] A. Hugi, R. Terazzi, Y. Bonetti, A. Wittmann, M. Fischer, M. Beck, J. Faist, and E. Gini, “External cavity quantum cascade laser tunable from 7.6 to 11.4 μm,” *Appl. Phys. Lett*. **95**, 061103 (2009).

[17] A. Bismuto, T. Gresch, A. Bächle, and J. Faist, “Large cavity quantum cascade lasers with InP interstacks,” *Appl. Phys. Lett.*, 93, 231104 (2008).

[18] R. Blanchard, C. Grezes, S. Menzel, C. Pflügl, L. Diehl, Y. Huang, J-H. Ryou, R. D. Dupuis, and F. Capasso, “Double-waveguide quantum cascade laser,” *Appl. Phys. Lett.*, **100**, 033502 (2012)

[19] J. Chen, R.G. Broeke, Y. Du, C. Jing, N. Chubun, P. Bjeletich, F.Olsson, S. Lourdudoss, R. Welty, C. Reinhardt, P.L. Stephan, S.J.B. Yoo, “Monolithically integrated InP-based photonic chip development for O-CDMA systems,” *IEEE Journal of Selected Topics in Quantum Electronics*, **11(1)**, 66 – 77 (2005).

[20] S.J.B. Yoo, S.Lourdudoss, W.T. Tsang, “Planar regrowth simplifies photonic integration of InP chips,” *Compound Semiconductor,* **15(2)**, 14-16 (2009).

[21] S. Blaser, D.A. Yarekha, L. Hvozdara, Y. Bonetti, A. Muller, M. Giovannini, and J. Faist, “Room-temperature, continuous-wave, single-mode quantum-cascade lasers at 5.4 μm,” *Applied Physics Lett*., **86**, 041109 (2005);

[22] Y. Bai, N. Bandyopadhyay, S. Tsao, E. Selcuk, S. Slivken, and M. Razeghi, "Highly temperature insensitive quantum cascade lasers", *Applied Physics Lett*. **97**, 251104 (2010).

[23] G.M. de Naurois, B. Simozrag, G. Maisons, V. Trinité, F. Alexandre, M. Carras, "High thermal performance of μ-stripes quantum cascade laser," *Appl. Phys. Lett.*, **101**, 041113 (2012).

[24] A. Lops, V. Spagnolo, G.Scamarcio, "Thermal modeling of GaInAs/AlInAs quantum cascade lasers," *J. Appl. Phys.,* **100**, 043109 (2006).

[25] S. Dhillon, J. Alton, S. Barbieri, C. Sirtori, A. de Rossi, M. Calligaro, H.E. Beere, D. Ritchie, "Ultra threshold current terahertz quantum cascade double-metal buried strip waveguides," *Appl. Phys. Lett.,* **87**, 071107 (2005).