



Deposited via The University of Sheffield.

White Rose Research Online URL for this paper:

<https://eprints.whiterose.ac.uk/id/eprint/246760/>

Version: Published Version

Article:

Mitchell, C.J., Zhou, L., Li, K. et al. (2026) Hybrid integration of quantum cascade lasers with germanium-on-silicon waveguides for mid-infrared sensing applications. Optics Express, 34 (20). 38302. ISSN: 1094-4087

<https://doi.org/10.1364/oe.600656>

Reuse

This article is distributed under the terms of the Creative Commons Attribution (CC BY) licence. This licence allows you to distribute, remix, tweak, and build upon the work, even commercially, as long as you credit the authors for the original work. More information and the full terms of the licence here:

<https://creativecommons.org/licenses/>

Takedown

If you consider content in White Rose Research Online to be in breach of UK law, please notify us by emailing eprints@whiterose.ac.uk including the URL of the record and the reason for the withdrawal request.



Hybrid integration of quantum cascade lasers with germanium-on-silicon waveguides for mid-infrared sensing applications

COLIN J. MITCHELL,^{1,*} LONGQI ZHOU,² KE LI,¹ DANIEL ADEYEMI,¹ AHMED OSMAN,¹ MILOS NEDELJKOVIC,¹ GLENN CHURCHILL,¹ JAMES C. GATES,¹ GRAHAM T. REED,¹ KRISTIAN M. GROOM,² JON HEFFERNAN,² AND GORAN Z. MASHANOVICH¹

¹Optoelectronics Research Centre, University of Southampton, University Road, Southampton, Hampshire SO17 1BJ, UK

²School of Electrical and Electronic Engineering, Sir Frederick Mappin Building, University of Sheffield, Mappin Street, Sheffield S1 3JD, UK

*c.j.mitchell@soton.ac.uk

Abstract: We present a scheme for hybrid integration of quantum cascade laser bars with germanium-on-silicon waveguides operating in the mid-infrared. The laser bars are flip-chip bonded onto a germanium-on-silicon target chip without active alignment, achieving end-fire coupling efficiencies of up to 50% (3.03 dB loss) in pulsed operation. Optical power estimates indicate over 50 mW is coupled into the waveguide. The passive alignment approach, combined with a CMOS-compatible photonic integrated circuit fabrication process, offers a scalable pathway to fully integrated mid-infrared photonic systems for sensing, free-space communications, and the realization of novel light sources.

Published by Optica Publishing Group under the terms of the [Creative Commons Attribution 4.0 License](#). Further distribution of this work must maintain attribution to the author(s) and the published article's title, journal citation, and DOI.

1. Introduction

Mid-infrared (MIR) silicon photonics, 2.5–20 μm [1], has become increasingly important due to the presence of strong molecular absorption lines in this spectral region. These absorption lines allow for identification of specific molecules based on individual chemical bonds. Applications such as widespread environmental monitoring (e.g., greenhouse gases and pollutants), security applications, and high-volume medical sensors for screening or monitoring of patients, require low-cost, compact systems. Developing such MIR systems for operation outside the laboratory would benefit significantly from the advantages offered by silicon photonic integration [2], including small footprint, light weight, scalability through mass production, and reduced cost [3,4]. Furthermore, on-chip integration of light sources will be crucial in enabling most of these applications, supporting fully integrated, practical MIR sensing solutions.

The indirect band gap of silicon prohibits efficient light emission and therefore the demonstration of silicon-based lasers. As a result, the integration of compound semiconductor lasers has become a critical technology for the realization of compact practical devices, with several competing approaches having been proposed [5]. The majority of this work has been performed at near-infrared (NIR) communication wavelengths where techniques such as wafer bonding, transfer printing [6–8] and direct growth [9–11] have been demonstrated, along with flip-chip bonding of processed lasers [12]. However, laser integration within the MIR region of the spectrum has not been widely addressed. Quantum cascade lasers (QCLs) are commonly used as light sources in the MIR because QCL heterostructures can be designed to have intersubband transitions with energy levels that correspond to photon emission at MIR wavelengths [13]. However, integrating

MIR lasers gives rise to some key additional challenges, such as the high power consumption of QCLs, which leads to thermal management issues, e.g. heat spreading laterally across the laser must be considered. Additionally, the limited transparency range of SiO₂ prevents the integration with widely used NIR SOI or SiN waveguides, therefore alternative mid-IR transparent waveguide platforms must be used instead (e.g. Ge-on-Si, SiGe-on-Si, or suspended Si [1]). At MIR wavelengths, optical mode sizes increase; consequently, the dimensions of these waveguides must be significantly larger than their NIR counterparts. This increased cross-section improves laser to waveguide alignment tolerance and enables good modal overlap in the vertical direction. However, it also requires thicker layers and deeper etches, necessitating the development of novel fabrication and integration processes for MIR applications.

Integration of a QCL with silicon photonic waveguides was first demonstrated on a silicon substrate [14] at 4.7 μm , by heterogeneously bonding a QCL gain block to a silicon-on-nitride-on-insulator (SONOI) photonic integrated circuit (PIC) platform. The light was evanescently coupled between the QCL waveguide and the SONOI waveguide. The fabrication process involved several steps being performed on the hybrid III-V/Si stack after bonding, which limits the use of this integration method to foundries/tools in which contamination between III-V and Si materials is accepted. Output powers of around 31 mW were reported in pulsed operation from a coupled waveguide at 20°C. Laser arrays of distributed feedback (DFB) and distributed Bragg-reflection (DBR) lasers were subsequently demonstrated and integrated with arrayed waveguide grating (AWG) multiplexers [15] on a silicon-on-insulator (SOI) platform.

The direct growth of QCLs on silicon substrates was first demonstrated with output power up to 50 mW per laser facet [16], emitting at a wavelength around 11 μm . Silicon (100) substrates 6° miscut towards [110] were utilized to reduce anti-phase domain formation [17]. Further development has included ICLs [18] at shorter wavelengths [19,20] demonstrating CW output powers of 40 mW at room temperature at 3.3 μm . In the far infrared, an InP-based QCL grown on (001) silicon, 4° miscut toward [110], with an InP epitaxial template [21] has demonstrated up to 4 W of output power from the laser facets at room temperature. These reports do not demonstrate the integration of lasers with MIR waveguides and large miscut angles are not compatible with manufacturing of silicon photonic devices. Integration issues remain, such as the induced roughness in the waveguide from the miscut angle, and critically thermal budgets where growth may include a desorbing process for an oxide, which can occur from 840°C for silicon dioxide [22]. This is outside the allowable limits for *in-situ* germanium waveguides where interdiffusion begins to occur and Ge surface roughness worsens at temperatures as low as 750°C [23]. It is also worth noting that the melting point of germanium is 938°C. High temperatures also need to be carefully considered with regard to the doping profiles required for circuit components. Critically, for silicon photonics this may require front-end growth of compound semiconductors, leaving substrates incompatible with CMOS facilities.

Recently, flip-chip placement of a DFB QCL at 7.2 μm has been demonstrated with peak CW power of 0.7 mW [24] coupled to a GOS waveguide. This system used a support structure and self-alignment by solder surface tension upon heating [25,26] with the solder deposited by screen printing. The final position of the chip, and hence yield, is highly dependent upon several factors including: tolerances of volume of deposited material, fabrication issues for solder wetting of the bond pads and friction-force ratios limiting the size of the chip for high yields.

In this paper, we present an alternative approach for integration using QCL bars to provide multiple sources simultaneously coupled to waveguides fabricated on germanium-on-silicon substrates. The technique can therefore be applied across the MIR, whilst representing a CMOS-compatible solution with a scalable route to volume production. It may be possible to use a laser bar simultaneously as a detector in one part of a photonic circuit and as an emitter in an adjacent region, with a performance trade-off between the two. Additionally, multiple lasers could be combined in a circuit to increase output power, or multiple wavelengths could be combined

[15] and selected using DFB QCL arrays, such as for free space absorption measurements [27]. The technique presented here uses no active alignment, instead relying on etched support structures for passive vertical alignment and the accuracy of the flip-chip bonder in the contact plane. Bonding alignment is provided directly from the facets along the length of the QCL bar and GOS waveguides using high magnification optics, eliminating potential fiducial-to-facet distance variation in the fabrication of either component. Solder is evaporated and patterned using standard processing tools. This allows full back-end integration of the QCLs entirely within cleanroom facilities, reducing the risk of contamination induced misalignment. Development of this approach yielded the first hybrid integration of a QCL on a silicon photonics platform in 2022 by the authors [28,29], but with only <1 mW of output power. Our new approach results in up to 50% peak coupling efficiency between the QCL and waveguide, and a maximum 54 mW of optical power in the waveguide in pulsed operation, making them suitable for use in sensitive MIR sensors. The wavelength utilized in this work, 5.7 μm , is important for medical sensing applications, such as therapeutic drug monitoring (TDM) of phenytoin in patients. Phenytoin is a drug that is used to control various types of seizures [30–32]. This wavelength is also of interest for the determination of estrogen levels [33] as used in the diagnosis of breast cancer [34]. Whilst the wavelength demonstrated here is relevant to specific clinical needs, it is important to note that this approach represents a technique that is transferable to other wavelengths across the MIR spectrum.

2. Integration design

Hybrid flip-chip bonding of processed QCLs to GOS circuits allows for the manufacture and optimization of the two individual components at dedicated, separate sites for group IV and compound semiconductor fabrication, eliminating cross-contamination issues. However, this requires a co-design approach incorporating the integration mechanics, alignment mechanism and related challenges.

Figure 1 shows schematic diagrams illustrating the relative positioning of the QCL bar, GOS waveguide, and contact pads to allow for alignment of the modes for end-fire coupling between the QCL and the GOS waveguide, whilst maintaining electrical contact. Support structures for the QCL were etched into the GOS to passively align the horizontal plane of the QCL bar to the plane of the waveguide, for vertical and angular alignment. To minimize alignment error from QCL processing, the support structures contacted an unprocessed area of the QCL surface. The etched support structure can be seen in Fig. 1(c) but is not shown in Fig. 1 (a/b) for schematic clarity. The GOS contact pad that connects to the QCL via a solder extends outside of the QCL footprint to enable contacts using electrical probes or bond wires. The waveguide includes two 90° bends (0.2 mm radius), intended to spatially separate the QCL input from the waveguide output, Fig. 1(b), in order to reduce the probability of emission from the laser facet interfering with the output measurement at the waveguide facet. A eutectic gold-tin alloy was used for the solder, so that it is in liquid phase during bonding to allow for the flat placement of the laser bar along the surface of the support structures. The solder was e-beam evaporated from an alloyed pellet source and patterned using conventional lithography and lift-off techniques. An excess of solder was deposited, larger than the designed gap between bond pads (500 nm) defined by the support structure. The excess solder provided reliable Ohmic contacts between the chips by allowing for up to 200 nm variation of the bond pad heights (either from etching silicon or metal deposition on either component) due to bonding in the liquid phase, allowing excess to flow laterally. The gold-tin solder had a composition of 25 wt% tin, giving a eutectic melting point of around 290°C [35] as the tin diffused out into the gold (eutectic composition is 20 wt% tin) into the gold pads to form robust contact interfaces. This resulted in a soldering temperature of 320°C to allow for pad wetting and thermal gradients across the samples. The full process flow is shown schematically in Fig. 2.

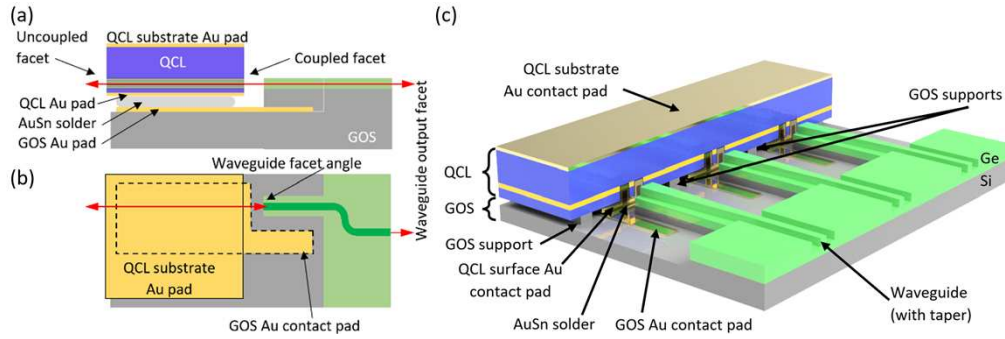


Fig. 1. (a) Side view of the QCL flip-chip bonded to the GOS chip showing the coupling region. (b) Top view of bonded QCL to GOS with the GOS gold pad shown as a dashed line. (c) QCL bars (top-left), processed GOS 6'' wafer (top-right) and schematic of the bonded device (bottom).

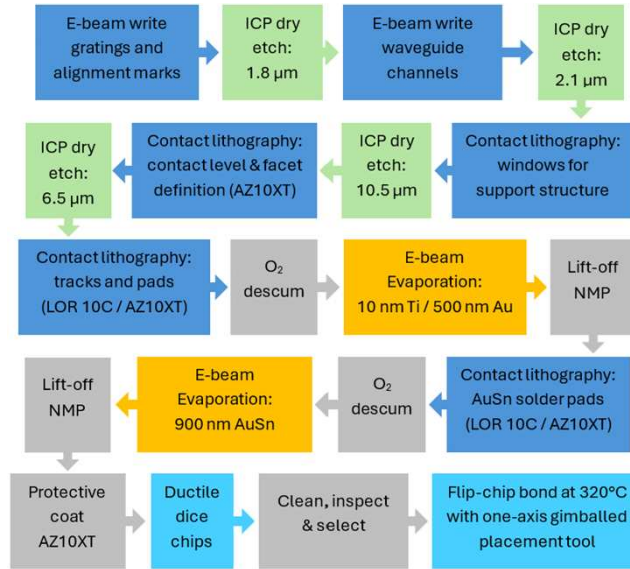


Fig. 2. Fabrication flow for the GOS chip and integration.

The etch order is important for three reasons. Firstly, forming the waveguides and grating couplers at the start enables the use of ZEP for e-beam lithography for the first two etch steps, avoiding the large step-coverage that would be required after the deeper later etches. The second issue to consider is forming the flat contact-pad-plane and also the trench around the supports which would act as a capturing reservoir for any excess solder that is provided by the two final etches. The first of these later two etches opens up a large window that will incorporate both the support and surrounding trench. The second masks the support area only in this window, whilst etching the surrounding trench area for a second time as well as the contact pad plane for the first time. This allows for flat contact pads/tracks beneath the QCL running towards the waveguide section, as shown in Fig. 1(a), with trenches running along either side as shown in Fig. 3. The third point to address is that this final etch also forms the input waveguide facet by etching across the waveguide channel giving a sharp profile (see Fig. 4). Importantly, this one-stage etch of the

facets down to the contact pad plane gives no physical step from successive etches to interfere with QCL placement. Vertical sidewalls were confirmed by FIB-SEM cross-section of other samples.

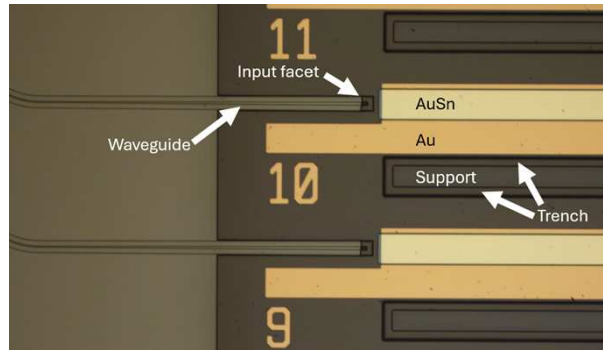


Fig. 3. Microscope image of final GOS chip, showing GOS waveguides, the waveguide input facets, support structures and metallization.

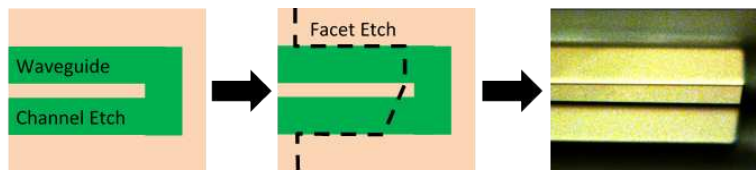


Fig. 4. Schematic of GOS waveguide input facet formation, and optical microscope image of the final device.

Measuring the coupling efficiency between the QCL and waveguide requires the output power of the QCL directed towards the waveguide to be known. As the QCLs are uncoated Fabry-Pérot (FP) lasers, the outputs from either facet are assumed to be equal, i.e. the power emitted from the coupling facet would be equal to the emitted power from the uncoupled QCL back facet. Hence, the chip was designed to be diced at the edge of the proposed laser bar position such that light emitted from the uncoupled QCL facet could be measured and then used as an estimate of the power from the coupled QCL facet (Fig. 1). This dice necessitated that the contact pads underneath the QCL routed towards, and adjacent, to the waveguides in a etched region, providing flat pads with probe access on the GOS chip.

The GOS chip was diced using a self-polishing ductile dicing process [36,37], which yields optical quality waveguide facets without additional polishing. The GOS waveguide input facets were etched as described above. Standard effective cutback loss measurement structures (i.e. variations of the waveguide length and bend number) were included on each die to assess the losses in the waveguide. Six of the waveguides were designed with output grating couplers to investigate the potential for future vertical coupling.

The GOS platform used in this work incorporates a 3- μm -thick germanium layer grown by Reduced Pressure Chemical Vapor Deposition (RPCVD) on (100) silicon [36]. Single mode GOS rib waveguides were designed for TM polarization, resulting in a width of 3 μm and a channel etch of 2.1 μm . The relatively thick waveguide layer, compared to SOI platforms, more closely matches the spot size of the laser in the vertical direction and so alleviates the need for 3D spot size converters to achieve good modal overlap for end-fire coupling. However, to allow for some lateral misalignment whilst maintaining good modal overlap, a simple 2D taper is

incorporated to expand the mode laterally, with the waveguide width increasing to $11\ \mu\text{m}$ over a length of $1\ \text{mm}$ to form a taper. Any higher order modes excited in the wide waveguide would be filtered out in the single mode waveguide that follows. Additionally, the waveguide facet was angled at 10° to reduce reflection back into the QCL.

The chips were integrated by placing the QCL on top of the GOS with the grown surface facing-down, using a FineTech Fineplacer Lambda flip-chip bonder with an alignment accuracy $\leq 0.5\ \mu\text{m}$ in the plane of the interface. Automated bonders with higher precision are available, demonstrating a route for scaling the process. Vertical and angular alignment out of this plane is not as accurate and is provided by the etched GOS supports. This alignment was achieved by placing the surfaces of the QCL and GOS in contact and parallel (i.e. flat) using the supports and a dedicated gimbaled placement head, as described in our previous work [38]. This method allows the GOS supports to contact the QCL along the full length of the laser bar ($14.5\ \text{mm}$ by $2.0\ \text{mm}$ bar), ensuring vertical alignment of all 24 lasers along the length of the bar at a pitch of $500\ \mu\text{m}$. Alignment between components was provided by viewing the two facets (QCL and waveguide) simultaneously through the beamsplitter of the bonder prior to contact, thus removing any error from fiducials to facet distances during QCL cleaving or facet definition on the GOS.

The MIR QCLs are based on a two-phonon resonance design [39] using the strain-balanced InGaAs/AlInAs material system grown by metalorganic vapor-phase epitaxy (MOVPE) at the National Epitaxy Facility, University of Sheffield. The material was processed into double-trench ridge waveguide structures with ridge width of $\sim 4.5\ \mu\text{m}$. Trenches penetrate through the active region to a depth of $6\ \mu\text{m}$, as shown in Fig. 5(a). The double trench scheme allows the unprocessed epitaxial surface in-between adjacent metal bond pads on the laser bar to be in contact with the support structures on the GOS substrate. To characterize the QCLs, uncoated FP lasers were mounted on diamond heat spreaders with the epitaxial surface facing up. Room temperature continuous-wave (RT-CW) operation was exhibited, with a threshold current density of $0.963\ \text{kAcm}^{-2}$ for a $3\ \text{mm}$ long cavity, and maximum power $>65\ \text{mW}$ per facet at a heatsink temperature of 15°C . RT-CW operation will degrade without the additional heatsinking described above, as is the case after the QCL has been integrated onto GOS. Additional heat spreading or active cooling can be added in such cases and is discussed in the final section. The measured optical far-field beam profile shown in Fig. 5(b) demonstrates a highly circular fundamental transverse mode, providing good beam quality, which is beneficial for effective waveguide coupling without 3D tapers. The FWHM fast- and slow-axis beam divergences are both around 55° .

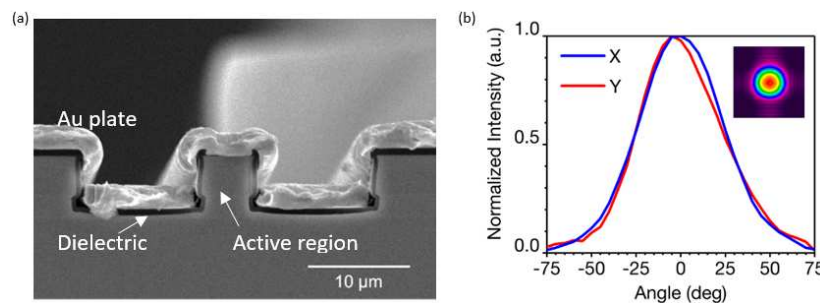


Fig. 5. (a) SEM image of a cross section in a $4.5\ \mu\text{m}$ wide double-trench QCL. (b) Measured X&Y-axis far-field beam profile, inset 2D color plot (measured using an Ophir Nano Scan pyroelectric scanning-slit beam profiler).

3. Coupling measurements

Initial characterization of the integrated device demonstrated consistent electrical connections. In pulsed mode operation, a far-field beam profile was measured from both a GOS waveguide facet and an output grating coupler (Fig. 6). The grating coupler demonstrates the potential for use with integrated detectors for a future sensor system but introduces additional losses that complicate the measurement of coupling, hence the use of the facet outputs for calculations in this work. The optical power emitted from both the QCL and GOS waveguide output facets (Fig. 7) was measured in pulsed operation (400 ns and 600 ns pulse widths). The emitted light was collected and collimated using a NA = 0.85 lens (Thorlabs C037TME-E) with anti-reflection coating and then focused on to a thermoelectrically cooled (TEC) VIGO InAsSb superlattice detector (PVIA-4TE-10.6-1 × 1) via a lens (Thorlabs LA7477-E2) with NA selected to match the detector acceptance angle. In the collimated section between the lenses, Thorlabs neutral density filters (NDF) were inserted to prevent saturation of the detector. The attenuation of the NDFs with nominal OD = 0.3, 1.0, 2.0 were experimentally determined using an identical QCL as the source.

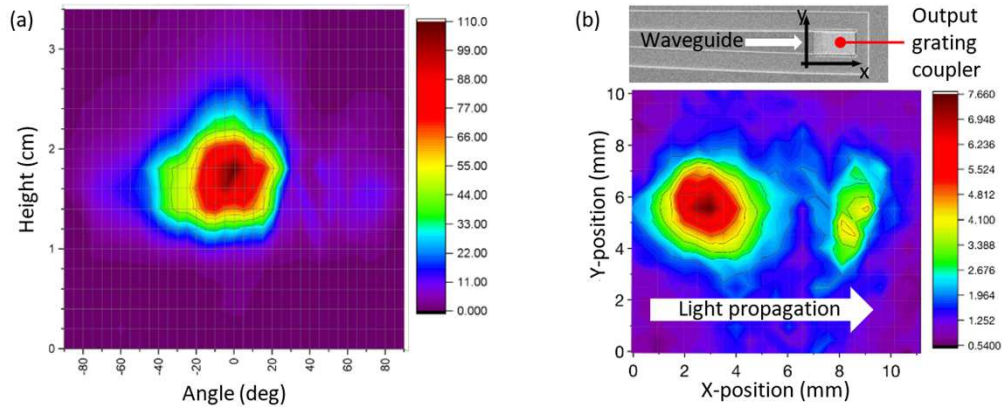


Fig. 6. (a) Far-field image of light output from waveguide facet measured at a distance of ~ 10 cm with a VIGO PVI-4TE-8 MCT-detector on a rotating stage, with height adjustment, (b) Light intensity distribution mapping in a 10mm*11 mm area using the same MCT detector at a height of 1 cm above the output grating coupler.

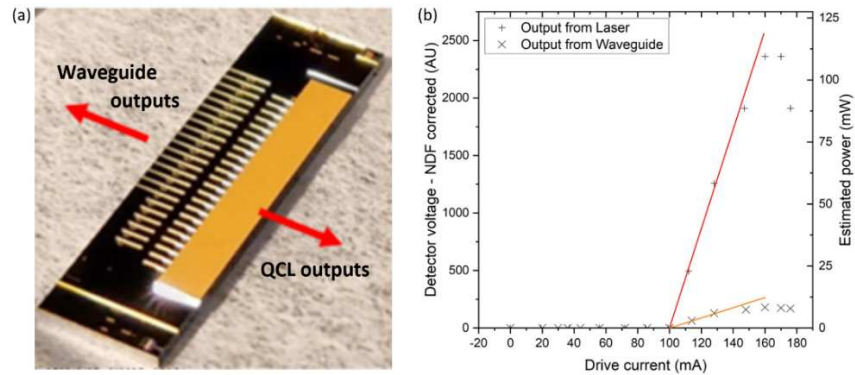


Fig. 7. (a) Integrated chip showing measured output facets. (b) QCL and GOS waveguide outputs from the integrated chip (pulse 400 ns).

The laser to waveguide optical coupling was calculated using Eq. (1), illustrated schematically in Fig. 8, where the Fresnel reflection loss ($L_r = 2.34$ dB) from the output of the germanium waveguide to free space was calculated using a 3D FDTD simulation in TM-mode operation to account for the dominant QCL mode. The calculated reflection loss is used to account for the reflection at the output of the germanium waveguide only. The measured output power from the waveguide is then converted to the optical power in the waveguide at the input as described in Fig. 8 using the reflection and waveguide losses.

$$L_c = -10 \cdot \log_{10} \left(\frac{P_{WG}}{P_{QCL}} \right) - L_p - L_b - L_r \quad (1)$$

Propagation and bend losses (L_p and L_b respectively) were derived from the measured transmissions of the passive test structures using the effective cut-back method. A QCL from the same batch mounted on a standard c-mount was used as the light source for these measurements. Light was coupled from a fiber into the GOS waveguides via end-fire coupling, and into an output fiber via grating couplers. The propagation loss was calculated as 8.6 dB/cm and the bend loss 9.8 dB/cm (0.38 dB/90° bend) as shown in Fig. 9. This gave a total loss through the waveguide and output facet of 5.85 dB. The high loss through the waveguide is attributed to the presence of strain-induced defects at the silicon-germanium interface, accentuated by the thermal cycling involved in the deep ICP-RIE etch. This will be improved in future devices by the use of cooler etch processes, which have been developed. The authors have demonstrated low loss in germanium waveguides at various wavelengths [40] and recent results in air clad waveguides close to 5 μm [41] show the potential for gains to be made.

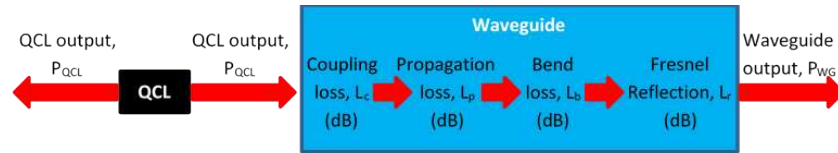


Fig. 8. Laser to waveguide optical coupling with losses.

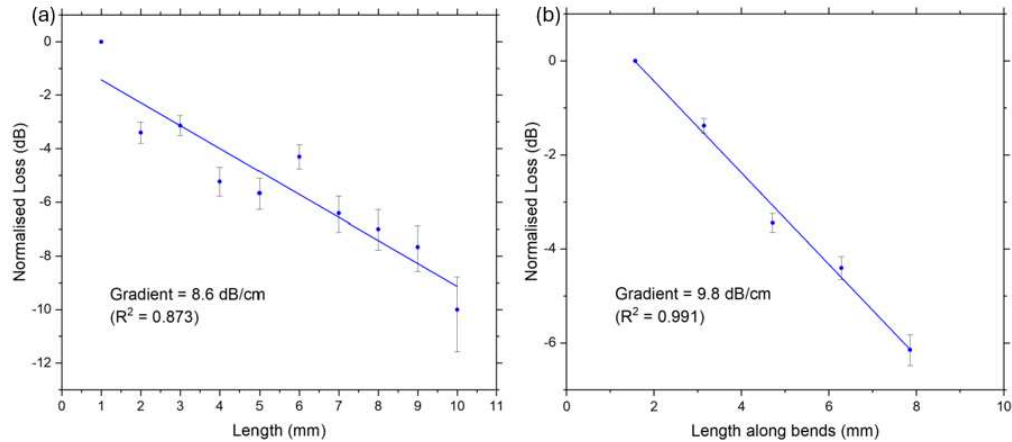


Fig. 9. Effective cut-back loss transmission measurements (a) Propagation loss. (b) Bend loss.

Misalignment of the facets inevitably produces a decrease in coupling efficiency. To explore this theoretically we have simulated how the mode overlap loss is affected by horizontal and

vertical misalignment between the QCL and GOS facet fundamental TM modes, using the Lumerical MODE FDE solver. We estimate that a 1 dB increase in mode overlap loss would be caused by a 1.20 μm horizontal offset or a 1.05 μm vertical offset.

The peak output-to-output coupling was calculated to be 12.9% (8.9 dB loss) from the data shown in Fig. 7(b). This data is from the device with the highest coupling, waveguide 11, with the integrated device mounted on a TEC at 10°C with a pulse width of 400 ns providing the optimum conditions. This is the coupling from the output facet of the waveguide, P_{WG} , as a fraction of QCL output power from the uncoupled facet of the QCL, P_{QCL} .

The QCL to GOS waveguide coupling efficiency at the interface of the two components, derived through the analysis above accounting for the losses in the waveguide and the reflection at the output of the germanium waveguide, is shown in Fig. 10. This produces a maximum value for laser to waveguide optical coupling of 50% (3.03 dB loss). As drive current increases, the coupling efficiency falls to 28%. This reduction could be indicative of laser heating producing thermal expansion or spectral changes in the FP cavity that affect the coupling, and with added device heating from the longer current pulse (600 ns) the highest coupling efficiency achieved was only 30%.

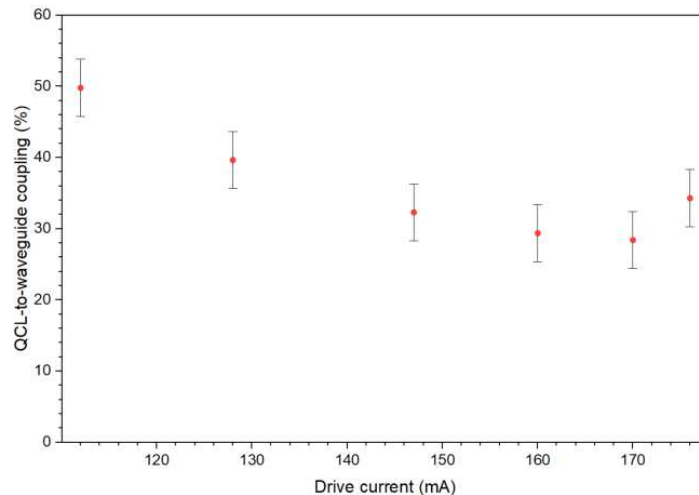


Fig. 10. Coupling efficiency plotted against drive current for pulse widths of 400 ns for the 11th laser in the array.

The data shown in Fig. 10 is from the QCL with the highest coupling efficiency on the bar. As the eleventh laser of twenty-four along the bar it was located close to the center. Along the bar, there were a mixture of end-fire and grating outcoupled lasers. Seventeen QCLs were coupled to GOS waveguides with end-fire outcoupling, six QCLs were coupled to GOS waveguides with grating couplers at the output, and by design one had no waveguide interface. Grating couplers were not used for the calculation of the coupling between QCL and waveguide, due to the larger uncertainty in calculating the coupling efficiency by separating out grating coupler and fiber losses. Of the seventeen end-fire QCLs, 100% of working devices coupled light with one QCL failing under initial electrical test. Away from the center of the bar, in both directions, the coupling efficiency fell, indicating that this was most likely due to thermal expansion mismatch rather than from rotational misalignment (yaw or roll). However, analysis of the full bar is complicated by changing facet angle and is not presented here. In order to give representative data a comparison can be made between the three 10-degree facet waveguides. This includes the laser described above near the center of the laser bar (and hence the center of alignment)

that demonstrated peak coupling efficiency. Here we see that the normalized fall in coupling efficiency from waveguide 11 to waveguide 14 is 21.7% (14.4% per mm), and 89.7% (16.3% per mm) to waveguide 22 close to the edge of the laser bar. The thermal expansion mismatch is produced by the difference in thermal expansion coefficient of the components and would 'freeze in' as the solder solidified providing a source of misalignment dependent upon distance from the point of alignment at the center. The potentially complex expansion mismatch (a function of tooling, components, and thermal gradients) can be experimentally measured and is expected to be repeatable. As such, incorporation of this expansion into the design of the waveguide spacing in future iterations could therefore increase and homogenize the efficiency along the bar to enable a stable manufacturing process.

In order to obtain an estimate of the optical output power in terms of mW, as opposed to the detector voltages plotted in Fig. 7(b), an identical QCL was placed in a conventional laser driver unit. Firstly, the power was measured in CW mode and then compared to the values of detector voltage using a standard chopper (simulating pulsed measurement). Quantifying the output power of the QCL and using the coupling efficiency at peak power, this equates to 54 mW of peak coupled power in the waveguide, demonstrating that such integrated QCLs have the potential to be used for integrated sensing systems.

4. Conclusions

In this paper, we have demonstrated a novel integration of QCL laser bars to a silicon photonics platform using CMOS-compatible processes. The efficient co-design of the components opens up the possibility of scaling up production for widespread use of this system for applications such as medical, environmental monitoring and security sensing across the MIR.

Flip-chip bonding eliminates the issues from the material interface associated with die/wafer bonded and monolithically grown structures, whilst the gold-tin alloy solder is an industrial standard for contacts and importantly acts as a critical heatsink (in conjunction with the gold-plated contacts) for the QCL directly at the epitaxial surface to the wide gold pads on the GOS.

Importantly, this approach allows for separate manufacture of the GOS and QCL components using optimal fabrication processes for each component with minimal back-end processing. Our hybrid approach using passive alignment of components, where the GOS contacts to unprocessed sections of the QCL to increase alignment accuracy, has demonstrated coupling into 11 μm wide waveguide facets along the length of a 14.5 mm laser bar. QCL performance has been demonstrated for pulsed operation after integration with a coupling efficiency of up to 50%. Further improvements could be made by applying additional heatsinking to the exposed substrate of the QCL, in addition to the heat spreading provided at the epitaxial surface shown above by gold plating on the QCL and gold-tin solder and gold pads on the temperature controlled GOS substrate. Additional heatsinking on the QCL substrate has been proven to dramatically improve performance [12], and may enable CW and higher power operation. Additionally, active cooling of the QCL substrate using miniature Peltier modules with contacts to control circuits on the GOS could be utilized if required.

A drop-off in coupling efficiency was noted away from the middle of the laser bar. This was expected and it is attributed to the mismatch in thermal expansion coefficients of the QCL and GOS chips. A coupling efficiency between the laser and waveguide of 3.5% was still achieved close to the edge, representing an estimated ~ 5 mW in the waveguide. The required spatial separation to correct for variable thermal expansion can be found experimentally by taking cross sections of the device and incorporated into future device designs.

These results demonstrate a path to achieve the integration of multiple sources simultaneously, tunable cavities integrated with QCLs [42], or the possibility of combining lasers at different wavelengths (within the gain spectra of the gain material) on a single bar. With further developments such as active cooling for the QCL integrated on the GOS chip, portable low-cost,

low-power light sources on chip could be realized and become a common tool in various sensing applications.

Funding. Engineering and Physical Sciences Research Council (EP/V047663/1, EP/W035995/1, EP/N00762X/1, EP/W020254/1); Royal Academy of Engineering (RF201617/16/33).

Disclosures. The authors declare no conflicts of interest.

Data availability. Data underlying the results presented in this paper are available with open access in [43].

References

1. A. Yadav and A. M. Agarwal, "Integrated photonic materials for the mid-infrared," *Int. J. Appl. Glass Sci.* **11**(3), 491–510 (2020).
2. C. J. Mitchell, T. Hu, S. Sun, *et al.*, "Mid-infrared silicon photonics: From benchtop to real-world applications," *APL Photonics* **9**(8), 080901 (2024).
3. R. Soref, "Mid-infrared photonics in silicon and germanium," *Nat. Photonics* **4**(8), 495–497 (2010).
4. S. Shekhar, W. Bogaerts, L. Chrostowski, *et al.*, "Roadmapping the next generation of silicon photonics," *Nat. Commun.* **15**(1), 751 (2024).
5. Z. Zhou, X. Ou, Y. Fang, *et al.*, "Prospects and applications of on-chip lasers," *eLight* **3**(1), 1 (2023).
6. G. H. Duan, S. Olivier, S. Malhouitre, *et al.*, "New Advances on Heterogeneous Integration of III–V on Silicon," *J. Lightwave Technol.* **33**(5), 976–983 (2015).
7. G. Roelkens, J. Zhang, L. Bogaert, *et al.*, "Micro-Transfer Printing for Heterogeneous Si Photonic Integrated Circuits," *IEEE J. Sel. Top. Quantum Electron.* **29**(3: Photon. Elec. Co-Inte. and Ad), 1–14 (2023).
8. M. A. Tran, D. Huang, J. Guo, *et al.*, "Ring-Resonator Based Widely-Tunable Narrow-Linewidth Si/InP Integrated Lasers," *IEEE J. Sel. Top. Quantum Electron.* **26**(2), 1–14 (2020).
9. Z. Wang, B. Tian, M. Pantouvaki, *et al.*, "Room-temperature InP distributed feedback laser array directly grown on silicon," *Nat. Photonics* **9**(12), 837–842 (2015).
10. Y. Xue, J. Li, Y. Wang, *et al.*, "In-Plane 1.5 μm Distributed Feedback Lasers Selectively Grown on (001) SOI," *Laser Photonics Rev.* **18**(1), 2300549 (2024).
11. Y. De Koninck, C. Caer, D. Yudistira, *et al.*, "GaAs nano-ridge laser diodes fully fabricated in a 300-mm CMOS pilot line," *Nature* **637**(8044), 63–69 (2025).
12. D. Coenen, H. Sar, H. Oprins, *et al.*, "Thermal Characterisation of Hybrid, Flip-Chip InP-Si DFB Lasers," *Micromachines* **14**(2), 381 (2023).
13. J. Faist, F. Capasso, D. L. Sivco, *et al.*, "Quantum Cascade Laser," *Science* **264**(5158), 553–556 (1994).
14. A. Spott, J. Peters, M. L. Davenport, *et al.*, "Quantum cascade laser on silicon," *Optica* **3**(5), 545–551 (2016).
15. E. J. Stanton, A. Spott, J. Peters, *et al.*, "Multi-Spectral Quantum Cascade Lasers on Silicon With Integrated Multiplexers," *Photonics* **6**(1), 6 (2019).
16. H. Nguyen-Van, A. N. Baranov, Z. Loghmari, *et al.*, "Quantum cascade lasers grown on silicon," *Sci. Rep.* **8**(1), 7206 (2018).
17. H. Kroemer, "Polar-on-nonpolar epitaxy," *J. Cryst. Growth* **81**(1–4), 193–204 (1987).
18. R. Q. Yang, "Infrared laser based on intersubband transitions in quantum wells," *Superlattices Microstruct.* **17**(1), 77–83 (1995).
19. A. Malik, A. Spott, E. J. Stanton, *et al.*, "Integration of Mid-Infrared Light Sources on Silicon-Based Waveguide Platforms in 3.5–4.7 μm Wavelength Range," *IEEE J. Sel. Top. Quantum Electron.* **25**(6), 1–9 (2019).
20. M. Fagot, D. A. Díaz-Thomas, A. Gilbert, *et al.*, "Interband cascade lasers grown simultaneously on GaSb, GaAs and Si substrates," *Opt. Express* **32**(7), 11057–11064 (2024).
21. S. Slivken and M. Razeghi, "High Power, Room Temperature InP-Based Quantum Cascade Laser Grown on Si," *IEEE J. Quantum Electron.* **58**(6), 1–6 (2022).
22. U. Johansson, H. Zhang, and R. Nyholm, "Thermal desorption of oxides on Si(100): a case study for the scanning photoelectron microscope at MAX-LAB," *J. Electron Spectrosc. Relat. Phenom.* **84**(1–3), 45–52 (1997).
23. R. C. F. Ang, J. S. Goh, L. Y. M. Tobing, *et al.*, "Annealing and passivation study of germanium on silicon (GOS) mid-infrared waveguide for sensing applications," *Sci. Rep.* **16**(1), 6909 (2026).
24. D. Wang, H. K. Kannoja, P. Jouy, *et al.*, "Innovative Integration of Dual Quantum Cascade Lasers on Silicon Photonics Platform," *Micromachines* **15**(8), 1055 (2024).
25. Y. Martin, S. Kamlapurkar, N. Marchack, *et al.*, "Novel Solder Pads for Self-Aligned Flip-Chip Assembly," *2019 IEEE 69th Electronic Components and Technology Conference (ECTC)*, (2019). pp. 528–534.
26. Y. Martin, J. S. Orcutt, C. Xiong, *et al.*, "Flip-Chip III-V-to-Silicon Photonics Interfaces for Optical Sensor," *2019 IEEE 69th Electronic Components and Technology Conference (ECTC)*, (2019). pp. 1060–1066.
27. B. G. Lee, M. A. Belkin, C. Pflugl, *et al.*, "DFB Quantum Cascade Laser Arrays," *IEEE J. Quantum Electron.* **45**(5), 554–565 (2009).
28. C. J. Mitchell, A. Osman, K. Li, *et al.*, "Hybrid integration methodology for quantum cascade lasers with germanium waveguides in mid-IR," *EPI Web Conf.* **266**, 01008 (2022).
29. C. J. Mitchell, A. Osman, K. Li, *et al.*, *Hybrid laser integration in the mid-IR for silicon photonics sensing applications*, (2023) SPIE.

30. S. H. Jang, Z. Yan, and J. A. Lazor, "Therapeutic drug monitoring: A patient management tool for precision medicine," *Clin. Pharmacol. Ther.* **99**(2), 148–150 (2016).
31. C. Hiemke, N. Bergemann, H. W. Clement, *et al.*, "Consensus Guidelines for Therapeutic Drug Monitoring in Neuropsychopharmacology: Update 2017," *Pharmacopsychiatry* **51**(01/02), 9–62 (2018).
32. E. Kozar, S. Parvez, B. A. Minassian, *et al.*, "How high can we go with phenytoin?" *Ther. Drug. Monit.* **24**(3), 386–389 (2002).
33. B. Zheng, W. Li, H. Li, *et al.*, "Separation and determination of estrogen in the water environment by high performance liquid chromatography-fourier transform infrared spectroscopy," *Sci. Rep.* **6**(1), 32264 (2016).
34. Z. Diamantopoulou, F. Castro-Giner, F. D. Schwab, *et al.*, "The metastatic spread of breast cancer accelerates during sleep," *Nature* **607**(7917), 156–162 (2022).
35. J. W. Ronnie Teo, F. L. Ng, L. S. Kip Goi, *et al.*, "Microstructure of eutectic 80Au/20Sn solder joint in laser diode package," *Microelectron. Eng.* **85**(3), 512–517 (2008).
36. M. Nedeljkovic, J. S. Penades, V. Mittal, *et al.*, "Germanium-on-silicon waveguides operating at mid-infrared wavelengths up to 8.5 μm ," *Opt. Express* **25**(22), 27431–27441 (2017).
37. P. C. Gow, G. M. Churchill, V. Vitali, *et al.*, "Mechanical dicing of optical quality facets and waveguides in a silicon nitride platform," *Electron. Lett.* **60**(5), e13138 (2024).
38. C. J. Mitchell, K. Li, R. Schachler, *et al.*, "Tooling and procedures for hybrid integration of lasers by flip-chip technology," *2020 IEEE 8th Electronics System-Integration Technology Conference (ESTC)*, (2020). pp. 1–7.
39. I. I. Zasavitskii, N. Y. Kovbasa, N. A. Raspopov, *et al.*, "A GaInAs/AlInAs quantum cascade laser with an emission wavelength of 5.6 μm ," *Quantum Electron.* **48**(5), 472–475 (2018).
40. G. Z. Mashanovich, C. J. Mitchell, J. S. Penades, *et al.*, "Germanium Mid-Infrared Photonic Devices," *J. Lightwave Technol.* **35**(4), 624–630 (2017).
41. R. Morgan, C. Heidelberger, D. Kharas, *et al.*, "Development and characterization of low-loss waveguides and top claddings for germanium-on-silicon mid-wave infrared integrated photonics," *Opt. Express* **33**(21), 44309–44322 (2025).
42. S. Radosavljevic, A. Radosavljević, C. Schilling, *et al.*, "Thermally Tunable Quantum Cascade Laser With an External Germanium-on-SOI Distributed Bragg Reflector," *IEEE J. Sel. Top. Quantum Electron.* **25**(6), 1–7 (2019).
43. C. Mitchell, "Dataset for: Hybrid Integration of Quantum Cascade Lasers with Germanium-on-Silicon waveguides for Mid-Infrared Sensing Applications," University of Southampton: Version 1, 29 Sept 2026, <https://doi.org/10.5258/SOTON/D3466>.