Hybrid integration methodology for quantum cascade lasers with germanium waveguides in mid-IR

Colin J. Mitchell[1,*], *Ahmed* Osman[1], *Ke* Li[1], *Jordi S.* Penadés[1], *Milos* Nedeljkovic[1], *Longqi* Zhou[2], *Kristian M.* Groom[2], *Jon* Heffernan[2], and *Goran* Mashanovich[1]

[1]Optoelectronics Research Centre, University of Southampton, University Road, Southampton, Hampshire SO17 1BJ, UK
[2]Department of Electronic and Electrical Engineering, Sir Frederick Mappin Building, University of Sheffield, Mappin Street, Sheffield, S1 3JD, UK

Abstract. Mid-infrared quantum cascade lasers (QCLs) operating around 5.7 μm have been integrated with germanium waveguides on silicon substrates. QCL bars have been designed and fabricated at the University of Sheffield for the purpose of integration. This hybrid approach uses flip-chip technology that has been successfully transferred from a silicon-on-oxide (SOI) platform working at communication wavelengths, demonstrating the flexibility of this approach. Integration challenges are introduced, and solutions discussed, leading to the next iteration of design presented here.

1 Introduction

Integration of optical sources is a critical technology for Silicon Photonics (SP). The combination of a silicon platform for a CMOS-compatible electro-optical system (or in this case germanium-on-silicon for mid-infrared), and conventional heterojunction compound semiconductor materials for the optical source, provides a 'best of both worlds' solution.

A range of approaches have been demonstrated such as heterogeneous growth of compound heterostructures on SP substrates, wafer bonding or token-printing of unprocessed or partially processed III-V materials, and hybrid integration of fully processed lasers.

Interest in hybrid integration of pre-fabricated III-V lasers on photonic chips has gained interest in recent years as placement tool have improved the potential for reliable placement of laser chips, and hence efficient coupling into waveguides from those chips. This is achieved directly, facet-to-facet, by flip-chip bonders (or novel placement techniques [1]), and may include the use of a spot size converter or coupling lens at the waveguide.

Alternatively, demonstrated hybrid solutions include stand-alone units, such as those produced by Luxtera for placement upon SP chips, that comprise a laser, lens, isolator and mirror for coupling to a grating.

The process described here is based upon the flip-chip bonding of III-V semiconductor laser bars, directly facet-to-facet. This was derived from technology transfer of previous work [2], investigating the integration of commercial telecommunications lasers with an SOI device. An example is shown below (Fig. 1.).

The QCLs utilised in this work were designed at the University of Sheffield National Epitaxy Facility, and were specifically matched to the requirements of the integration methodology presented here. They adopt a double-phonon resonance active region design, based on strain-compensated $In_{0.6}Ga_{0.4}As/Al_{0.58}In_{0.42}As$ material system grown by MOVPE. 4.5 μm wide ridge waveguide Fabry-Perot lasers were fabricated with electroplated top contacts. 2 mm long lasers exhibit CW lasing at room temperature with tens of mW output power.

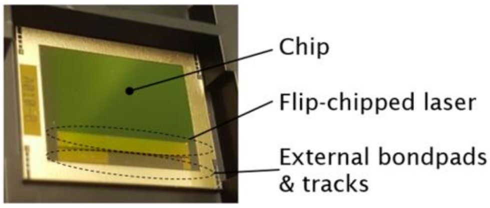

Fig. 1. Commercial laser integrated on SOI at Southampton

2 Flip-chip bonding

Flip-chip bonders produce <0.5 μm positioning accuracy in the plane of the interface, and rotational alignment in that plane is a function of x-alignment (Fig. 2.) at either end of a chip, longer chips increase accuracy. Importantly, systems can be automated for industrial manufacturing. A manual FineTech Fineplacer was used in this work

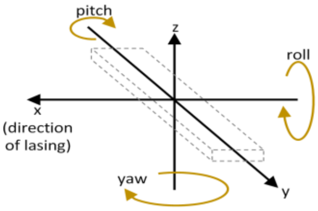

Fig. 2. Degrees of freedom and alignment

However, the vertical and rotational alignments provide challenges. Rotational alignment can be

---

[*] Corresponding author: c.j.mitchell@soton.ac.uk

addressed by the use of gimballed placement tools (Fig. 3.), but with mechanical size limitations requiring process design to incorporate both gimbals and high magnification optics for manual alignment in different axes [2], as shown below (Fig. 4.).

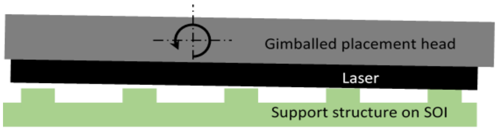

Fig. 3. Rotation alignment through gimbal

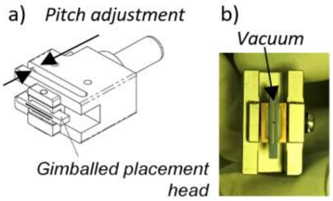

Fig. 4. Rotation alignment through focus a) pitch adjustment schematic, b) placement tool (FineTech GmbH & Co) with gimbal and pitch adjustment

Vertical alignment is most easily addressed by using a support structure fabricated on the SP chip, which is in contact with the unprocessed laser top-epitaxial surface at bonding [1-2], as shown in Fig. 3. in conjunction with a gimballed placement tool. Alternatively, surface tension of a solder material can be used, either with or without a support structure. This requires very high accuracy deposition of the solder and fabrication of wetting areas on the laser. When only a support structure is used, as here, the tolerances on solder material deposition (gold tracks, and gold-tin solder) parameters are reduced.

3 Germanium QCL integration

Germanium waveguides and gratings (3-µm germanium layer on silicon) were formed by e-beam lithography and ICP etch. QCLs were flip-chip bonded to the substrate using AuSn solder - evaporated and patterned by optical lithography. Initial data demonstrated coupling to a germanium waveguide, via a grating, in pulsed operation. Developing experimental setup, particularly the cooling head design yielded 30-fold improvement in intensity and operation up to 50% duty cycle at 10°C. Assessment of both components, and their integration, demonstrated routes for further development.

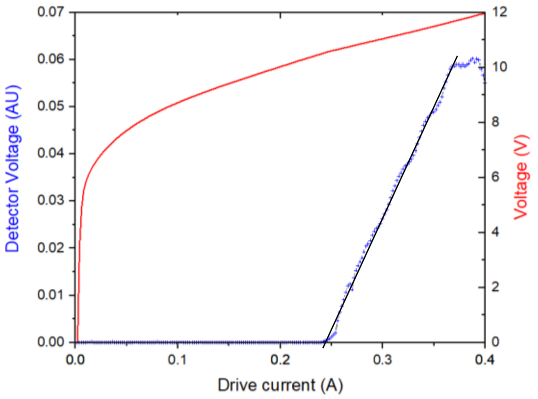

Fig. 5. L-I-V measured (10°C) at germanium grating via fibre

4 Holistic design iteration

Several areas for enhancement were identified on either component individually, and as a single integrated device. A holistic design approach addressing both components simultaneously is critical for such systems, and will be discussed. Processing developments, e.g. vertical ICP etch (Fig. 6.) for the waveguide input facet were also optimised; and original grating designs developed.

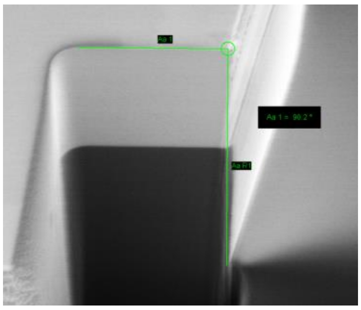

Fig. 6. FIB image of facet showing 90.2° vertical over 8 µm

This intrinsically linked holistic approach has enabled the next generation design (currently in fabrication) to be developed. This includes real-time fibre monitoring from the other side of the QCL (Fig. 7.), whilst monitoring the outputs via gratings and polished facets.

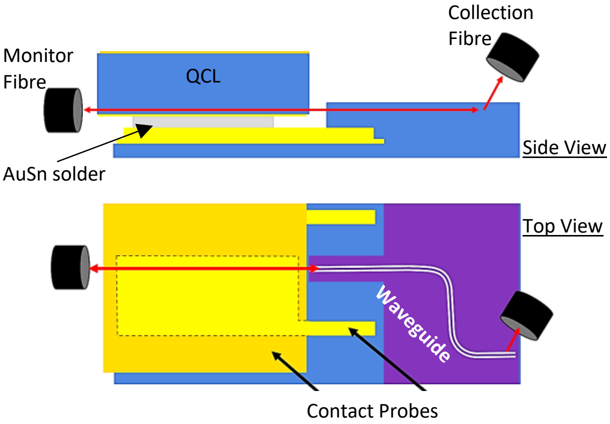

Fig. 7. Latest design with real-time monitor of QCL

The authors would like to acknowledge ESPRC (UK) for funding the Future Photonics Hub programme, and FineTech GmbH & Co for their collaboration.

References

1. Y. Martin, S. Kamlapurkar, N. Marchack, J. Nah and T. Barwicz, IEEE 69th Electronic Components and Technology Conference (ECTC), 2019
2. C.J. Mitchell, K. Li, R. Schachler, A. Khokhar, X. Chen, S. Stanković, X. Wang, N.P. Sessions, K.M. Grabska, D.J. Thompson, C. Daedlow, G.T. Reed, J.S. Wilkinson, IEEE 8th Electronics System-Integration Technology Conference (ESTC), 2020