Monolithic integration of buried-heterostructures in a generic integrated photonic foundry process

Citation for published version (APA):

DOI:
10.1109/JSTQE.2019.2927576

Document status and date:
Published: 01/09/2019

Document Version:
Accepted manuscript including changes made at the peer-review stage

Please check the document version of this publication:
• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
• The final author version and the galley proof are versions of the publication after peer review.
• The final published version features the final layout of the paper including the volume, issue and page numbers.

Link to publication

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

• Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
• You may not further distribute the material or use it for any profit-making activity or commercial gain
• You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the “Taverne” license above, please follow below link for the End User Agreement:
www.tue.nl/taverne

Take down policy
If you believe that this document breaches copyright please contact us at:
openaccess@tue.nl
providing details and we will investigate your claim.
Monolithic Integration of Buried-Heterostructures in a Generic Integrated Photonic Foundry Process

Valeria Rustichelli, Cosimo Calò, Florian Lemaitre, Stefanos Andreou, Nicolas Michel, Frederic Pommereau, Huub Ambrosius and Kevin Williams

Abstract—This work demonstrates the integration of buried-heterostructure (BH) lasers and semiconductor optical amplifiers (SOAs) in a generic photonic foundry platform. The process-flow adaptations necessary for their integration with existing building blocks are presented. BH Fabry-Perot lasers fabricated within the platform are fully characterized and compared with shallow-ridge (SR) lasers already available as a standard building block. SR lasers were fabricated on the same wafer sharing the same layer stack. BH lasers showed a reduction in threshold current of 60% and a reduction in thermal resistance of 40%. The full integration is then validated by the characterization of a compact arrayed waveguide gratings (AWG) laser-based transmitter consisting of eight BH-SOAs and a deep-ridge waveguide. A side-pump arrayed waveguide grating (AWG) laser-based transmitter integration is then validated by the characterization of a complete transmitter. BH lasers showed a reduction in threshold current of 60% and a reduction in thermal resistance of 40%. The full integration is then validated by the characterization of a compact arrayed waveguide gratings (AWG) laser-based transmitter consisting of eight BH-SOAs and a deep-ridge waveguide. A side-pump arrayed waveguide grating (AWG) laser-based transmitter integration is then validated by the characterization of a complete transmitter. BH lasers showed a reduction in threshold current of 60% and a reduction in thermal resistance of 40%. The full integration is then validated by the characterization of a compact arrayed waveguide gratings (AWG) laser-based transmitter consisting of eight BH-SOAs and a deep-ridge waveguide. A side-pump arrayed waveguide grating (AWG) laser-based transmitter integration is then validated by the characterization of a complete transmitter. BH lasers showed a reduction in threshold current of 60% and a reduction in thermal resistance of 40%. The full integration is then validated by the characterization of a compact arrayed waveguide gratings (AWG) laser-based transmitter consisting of eight BH-SOAs and a deep-ridge waveguide.
the first selective regrowth consists of a semi-insulating semiconductor, usually Fe-doped InP. The second non-selective regrowth consists of the p-InP cladding and ternary layers. In [13], 25.8 Gbps/second Modulation of FP SI-BH DFB lasers is demonstrated. Optical output power was more than 10 mW at 85°C.

Blocking-junction and SI-BH components block the leakage currents more efficiently than BRS devices, but two regrowth steps are required. In this work we chose to integrate BRS lasers as only one regrowth is required. While most of the BH literature has been focused on discrete BH components, a small number of reports have shown active/passive integration. Hybrid integration of BRS-BH and a SiO₂ AWG was demonstrated by Debregeas et al. in [14]. Monolithic integration of BH-SOA and a DR AWG was achieved by Suzaki et al. [15]. In 2015 Suzuki et al. [16] reported on a tunable light source composed by BH-DFB lasers and a DR AWG.

In this work we present the implementation of BRS BH lasers and amplifiers in a foundry process which includes a comprehensive range of DR and SR active and passive components [1], [17]. Specifically we report on the integration of BRS BH lasers and SOAs developed at III-V lab in an InP generic photonics platform developed at TU/e [1], [2]. The TU/e process is commercialised by Smart Photonics: jeppix.eu. PICs including both BH and ridge components have been designed and fabricated. To the best of our knowledge this is the first time that BH components are integrated in a generic photonic platform. This is also the first time that BH and SR lasers sharing the same layer stack and process flow are compared.

The process development for the integration of the BH BB addresses three key challenges: (i) ensuring that the fabrication of the generic BBs of [1] is not impaired and thus guarantee the ridge BBs performance; (ii) minimizing the number of extra regrowths and lithography steps to two; (iii) ensuring a good alignment between the two mask sets used for the BH and ridge BBs definition thus reducing reflections and losses [18].

The paper is structured as follows: an overview on the generic platform is given in Section II. Section III presents the process development necessary to integrate BH lasers into the platform; Section IV presents the characterization of the fabricated Fabry-Perot BH lasers in terms of R₀, threshold current (Iₜh), slope efficiency. A comparison is made with co-fabricated SR active devices already integrated in the platform. In Section V, the integration is validated by the characterization of an AWG laser with a combination of active BH and SR/DR passive building blocks. LI curves, spectrum analysis and linewidth measurements are presented.

II. GENERIC PHOTONIC INTEGRATION PLATFORM

The generic integration platform comprises a number of key building blocks which can be configured to construct application specific circuits. Fig.2 shows the cross sections of the BBs used in this work.

Deep ridge (DR) passive waveguides are shown in Fig. 2a: DR waveguides are used when a high refractive index contrast

---

**Fig. 2:** (left) Schematic representation of building blocks available in a generic platform and (right) a schematic representation of the BRS-Buried-Heterostructure used for this work. Blue colors are used for InP (n-doped and p-doped), green for the separate confinement heterostructure layers and red for the core layer containing the quantum well stack and for the ternary contact layer.

III. BURIED-HETEROSTRUCTURE INTEGRATION

The process flow adaptations for the BH BB integration are now presented in detail, highlighting how the different challenges have been addressed. Fig.3 reports a schematic overview of the process.

In Fig. 3a, four InGaAsP QWs are sandwiched between Q1.25 material. The total separate confinement heterostructure thickness is 500 nm. In Fig. 3b, the active regions are covered and the areas reserved for the passives waveguides are etched away by wet-etching. In Fig. 3c, the passive layer stack is grown. These steps are the same as the process flow described in [1].

The BH waveguides are subsequently defined and etched (Fig. 3d). A set of large area features (referred to as shadow area) is also defined in the same mask layer to prevent unwanted etching of the active and passive layer stacks. Ridge BBs can be defined inside this area without the need of an extra regrowth. This area has to be large enough to contain
all SR and DR BBs of the design (for example an AWG) that are defined in following step.

The p-InP regrowth is then performed (Fig. 3e). This regrowth (referred to as BRS/cladding regrowth) has a double function: on the BH waveguides it serves as a burying layer, and on the rest of the wafer it serves as a cladding layer. The p+ doped ternary (InGaAs) layer which is necessary for the contact is also grown within this step. Next, SR and DR waveguides are defined within the same lithography step, providing a perfect DR/SR alignment. A set of masks is then used to define the three etch depths. The cross-section after these steps is shown in Fig. 3f. To ensure a good alignment between the BH/shadow lithography (Fig. 3d) and the SR/DR lithography (Fig. 3f), a Canon FPA-3000 i4 stepper lithography tool is used (i-line 365 nm). This tool provided a mask overlay error of less than 200 nm, ensuring low losses and reflections as explained in [8].

Subsequently planarization is performed by polyimide coating in order to reduce the height differences on the chip and therefore facilitate the subsequent lithographic steps. Finally metal contacts are defined on the top and on the back-side of the wafer. Fig. 3g shows the schematic cross-section after planarization and metallization. In order to reduce leakage current, $H^+$ implantation is performed on the side of the BH waveguides (Fig. 3h).

The process flow is implemented for a 2-inch InP substrate and a mask set comprising the range of building blocks shown in Fig. 2. Fig. 4 shows a scanning electron microscope (SEM) picture of the top view of the butt-joint interface between a BH waveguide (left waveguide, cross-section A) and a DR waveguide (right waveguide, cross-section B). The DR waveguide is defined on the side by two 10-µm large trenches that are patterned in the shadow area. To reduce reflections and losses at the interface, BH and DR waveguides are tapered out to 4 µm and 4.25 µm respectively and the interface is tilted by 15° as described in [8]. From the SEM picture we can observe a mask alignment between BH and SR layers within 100 nm.
Thanks to the shadow approach and thanks to the shared BRS/cladding regrowth, the total number of growths did not change respect to the process presented in [1] and only two extra lithographies were added.

IV. EXPERIMENTAL COMPARISON OF BURIED-HETEROSTRUCTURE AND SHALLOW-RIDGE LASERS

BH and SR waveguide devices are fabricated on a 2-inch wafer following the process explained above. These are now characterized in terms of $R_{th}$ and $I_{th}$. Different cells with arrays of BH and SR FP lasers 1.75 μm-wide were fabricated. The simulated confinement factor $'l'$ in the quantum wells is 8.3% and 7.8% for the SR and BH waveguides respectively.

FP cavities were then defined by cleaving the cells at different lengths (690 μm, 890 μm and 1100 μm). In this work we analyze lasers coming from two different cells (one with BH lasers and one with SR lasers).

A. Thermal resistance of BH and SR building blocks

Heating in semiconductor lasers is a critical phenomenon that affects the $I_{th}$ and internal efficiency of the device. When injecting electrical power in a laser, part of this power will be dissipated through the Joule heating and the temperature of the active core will increase. To evaluate how efficiently a laser dissipates the heat, the thermal resistance parameter $R_{th}$ is used. $R_{th}$ is defined as the ratio of temperature rise relative to the substrate and the input electrical power.

Measured values of $R_{th}$ of SR and BH lasers are now reported and compared with simulated results obtained by using the model developed in [9]. $R_{th}$ is measured for BH and SR lasers of different lengths and same width. All the measured devices are FP lasers with cleaved facets. The light is collected with a lensed optical fiber.

The extraction of the thermal resistance is performed by measuring the red shift of a selected longitudinal mode as a function of the increasing injected electrical power $\Delta P$. By increasing the injected power, the temperature inside the active layer will also increase by $\Delta T$ and the increase of temperature will determine the redshift $\Delta \lambda$ of the peak. Thermal resistance is then calculated by using the following formula [19]:

$$R_{th} = \frac{\Delta T}{\Delta P - P_{opt}} = \frac{\Delta \lambda}{\Delta P - P_{opt}} = \frac{\Delta \lambda}{\Delta P - P_{opt}}$$  \[\eqref{1}\]

where $P_{opt}$ is the emitted optical power. $\frac{\Delta \lambda}{\Delta P}$ is measured by changing the substrate temperature at a constant injected power of 0.16 W.

Measured and simulated values are presented in Fig. 5 showing a good agreement [9]. For BH, the measured $R_{th}$ is 27.5 K/W, 28.7 K/W and 36.3 K/W for 690 μm, 890 μm and 1100 μm cavity lengths respectively. For SR, the measured $R_{th}$ is 40.3 K/W, 45.4 K/W and 62 K/W for 690 μm, 890 μm and 1100 μm cavity lengths respectively.

An average improvement of 40% in $R_{th}$ is seen in three of the BH lasers. This means that the change in temperature in the active BH laser is 40% less with respect to the SR laser when the same electrical power is injected.

B. Threshold current and slope efficiency analysis

Thanks to the lateral confinement of current, BH lasers are expected to have a more efficient current injection and therefore a lower threshold current [4].

Light-Current (LI) characteristics are recorded for BH and SR lasers of different lengths (690 μm, 890 μm, 1100 μm) and a width of 1.75 μm. The investigated devices are FP lasers, with cleaved facet. The FP lasers are bonded with Epotek on a copper chuck placed on a Peltier to control the temperature. Light is collected with a large area photodetector and measurements are performed in continuous wave (CW). Lasers are measured at 12°C, 25°C, 35°C and 45°C to study the temperature dependence performance. The recorded LI characteristics at different temperatures for 690 μm-long FP lasers are shown in Fig. 6a and Fig. 6b for BH and SR lasers respectively. A reduction of $I_{th}$ is clearly observed for BH lasers.

The extraction of $I_{th}$ is performed by finding the peak of the second derivative of the LI curve. By increasing the temperature, $I_{th}$ varies from 7 mA to 14 mA for BH lasers and from 13 mA to 23 mA for SR lasers. An improvement of 60% is achieved in BH FP lasers at 18°C. The slope efficiency decreases from 138 mW/A to 101 mW/A for BH and from 120 mW/A to 93 mW/A for SR.

The characteristic temperature $T_0$ is used to describe the temperature sensitivity of the device. It is defined by $T_0 = \Delta T/log(\Delta J_{th})$ where $\Delta T$ is the change in temperature and $J_{th}$ is the associated change of the threshold current density. The threshold current density $J_{th}$ is defined by dividing threshold current by the laser p-contact area (width $\times$ length). Fig. 7 shows $J_{th}$ for BH and SR lasers measured above. $T_0$ is found to be 44 K and 52 K for BH and SR lasers respectively.

V. ARRAYED WAVEGUIDE GRATING LASER

An AWG-Laser (AWGL) with 8 BH gain sections connected to the input waveguides is fabricated to demonstrate the
integration of BH components with a set of passive BBs. Design and characterization are now reported.

A. Design and fabrication

The mask layout of the AWGL is shown in Fig. 8a. Referring to the steps shown in Fig. 3, the green layer is used in step-c (BH waveguide and shadow definition), the blue layer in step-d (ridge waveguide definition) and the orange layer in step-g (metallization). The mask containing the AWG and all the other SR and DR BBs (blue layer) are defined inside the shadow area (green layer) without the need to modify the BBs in the foundry process design library. Both BH and SR/DR waveguides are tapered out at the BH-DR/SR interface to decrease reflections.

The laser cavity is defined by one cleaved facet and one multimode-interference reflector (MIR) [17] providing estimated reflectivities of 33% and 50% respectively. For the designed laser, the round-trip cavity length (SOA + AWG + input/output waveguides) is 8 mm. The output waveguide is defined as an SR passive waveguide building block with a 7° off-normal angle at the facet. This is also tapered to 3 µm to ensure low fundamental mode reflections. Assuming a negligible contribution of the buried-ridge transition, the total losses inside the cavity of the AWGL are estimated to be 6.1 dB (5 dB from the AWG [1], 1 dB from the MIR [2] and 0.1 dB from the shallow-deep transition [2]).

The AWG is designed to provide a channel spacing of 100 GHz (0.8 nm) and a free spectral range (FSR) of 900 GHz (7.2 nm). A microscope picture of the fabricated chip is shown in Fig. 8b. On the right side we can see the array of 500 µm-long BH-SOAs. The AWG is placed inside the shadow area of which the border is visible.

B. LI analysis

The AWGL chip is cleaved on a cell of 4.6 mm x 4.0 mm and the LI characteristic of each channel is recorded.
C. Spectrum and Linewidth Characterization

In order to record the optical spectrum of the laser, the experimental set-up is the same as described for the LI measurements, but the light is collected with a lensed fiber. The collected light is coupled to a high-resolution (0.16 pm) Optical Spectrum Analyser (APEX AP2041A). Fig. 10 shows the setup and the chip under test.

Each SOA was driven from 20 mA to 200 mA. For each SOA, a value of current that ensures the lasing in the first order of the AWG is chosen. For the analyzed AWGL, a single mode operation in the first order of the AWG is obtained for each SOA. Fig. 11 shows eight overlaid spectra for the AWGL. Current is injected into every SOA one at the time and the spectra are recorded. All the spectra are finally superimposed. The measured FSR is 907 GHz and the channel spacing is 99.8 GHz, as expected by the design. Fig. 12 shows the spectrum for channel 7, recorded at 18°C with an injected current of 125 mA. The recorded optical spectrum shows a side mode suppression ratio (SMSR) of 57 dB for the best case for the best channel ensuring a single mode operation of the laser.

The linewidth of the AWGL source is measured at 18°C with a delayed-self-heterodyne setup with a delay line of 25 km, a resolution of 50 kHz and a video bandwidth of 10 kHz.

The chip is placed on a Peltier cooled heat sink at constant temperature of 20°C. The current is injected in each channel, one by one, by an electrical probe and light is collected by using a large area photo-detector. Measurements are performed in CW operation.

Fig. 9 shows the measured LI curves of the 8 channels of the AWGL (channels are numbered from 1 to 8 starting from the top). A threshold current of 15 mA is measured at 18°C for channels 2 to 7 and 25 mA for channel 1 and 8. The outermost channels of cyclic AWGs are known to have high losses [20].

The threshold current dependence on temperature is also investigated. A change in threshold current from 15 mA to 17 mA is observed when temperature changes from 18°C to 25°C.

C. Spectrum and Linewidth Characterization

In order to record the optical spectrum of the laser, the experimental set-up is the same as described for the LI measurements, but the light is collected with a lensed fiber. The collected light is coupled to a high-resolution (0.16 pm) Optical Spectrum Analyser (APEX AP2041A). Fig. 10 shows the setup and the chip under test.

Each SOA was driven from 20 mA to 200 mA. For each SOA, a value of current that ensures the lasing in the first order of the AWG is chosen. For the analyzed AWGL, a single mode operation in the first order of the AWG is obtained for each SOA. Fig. 11 shows eight overlaid spectra for the AWGL. Current is injected into every SOA one at the time and the spectra are recorded. All the spectra are finally superimposed. The measured FSR is 907 GHz and the channel spacing is 99.8 GHz, as expected by the design. Fig. 12 shows the spectrum for channel 7, recorded at 18°C with an injected current of 125 mA. The recorded optical spectrum shows a side mode suppression ratio (SMSR) of 57 dB for the best case for the best channel ensuring a single mode operation of the laser.

The linewidth of the AWGL source is measured at 18°C with a delayed-self-heterodyne setup with a delay line of 25 km, a resolution of 50 kHz and a video bandwidth of 10 kHz.

Fig. 9: LI measurements of the 8 channels of the AWGL. The channels are injected one by one.

Fig. 11: Overlaid optical spectra of the AWG laser with bias current optimised for side mode suppression.

Fig. 12: Optical spectrum of channel 7 at 18°C showing an SMSR of 57 dB.

Fig. 10: Fabricated chip and optical setup used for optical spectrum measurements.
The measured linewidth is 1.5 MHz.

VI. CONCLUSIONS

We demonstrated the successful integration of BH lasers into an InP foundry platform. The process flow for the integration requires only the addition of two lithography steps and one etching step and no extra regrowth is needed. The buried-heterostructure lasers showed a reduction in threshold current of 60%, and a reduction of 40% of thermal resistance with respect to shallow ridge lasers. To the best of our knowledge, this is the first time that BH lasers are successfully integrated into a generic platform and compared with co-fabricated SR lasers. Platform integration is demonstrated with the successful realisation of an AWG-laser including BH active sections.

VII. ACKNOWLEDGEMENT

The authors wish to thank Barry Smalbrugge, Robert van de Laar and René van Veldhoven from Nanolab@TU/e and Olivier Parillaud, Antoine Elias and Florence Martin from III-V lab for their contribution.

REFERENCES


a spectrometer with an imprinted microfluidic device’. In October 2014, she joined Prof. Kevin Williams group at TU/e to work on the integration of Buried-Heterostructures lasers and amplifier in the COBRA generic platform. Her PhD is in collaboration with the III-V laboratory in Palaiseau, France.

**Cosimo Calò** Cosimo Calò was born in Terlizzi, Italy, in 1988. He received the joint M.Sc. degree in Micro- and Nanotechnologies for Integrated Systems from Grenoble INP, France, Politecnico di Torino, Italy, and EPFL, Switzerland, in 2011 and the Ph.D. degree from Université Pierre et Marie Curie, Paris, France, in 2014. From 2011 to 2015, he was with the CNRS Laboratory for Photonics and Nanostructures, Marcoussis, France, where he has worked on the fabrication and the characterization of quantum dot based mode-locked lasers for optical frequency comb generation. From 2015 to 2016, he was with Telecom SudParis, Evry, France, where he worked as Postdoctoral Researcher on the development of optical coherence tomography systems for biometric applications. Since August 2016, he has been with III-V Lab, a joint laboratory of Nokia Bell Laboratories, Thales Research and Technology and CEA-LETI, Palaiseau, France, where he is currently working as researcher in laser fabrication and photonic integration and he is in charge of the electron beam lithography facility.

**Florian Lemaitre** received the M.Sc. degree in engineering in 2014 from the Grenoble INP - Phelma engineering school, Grenoble, France, and he is currently working toward the Ph.D. degree in the Photonic Integration (PhI) group, Department of Electrical Engineering, Eindhoven University of Technology (TU/e), The Netherlands. His research interests include the development of selective area growth for photonic generic integration technology, which aims at providing bandgap tuning for active building blocks of the platform.

**Stefanos Andreou** received the B.Sc. in Electrical Engineering from the Aristotle University of Thessaloniki in 2012 and M.Sc. degrees from Eindhoven University of Technology, Eindhoven, The Netherlands 2015. Since 2015, he has been working toward the Ph.D. degree in the Photonic Integration group, Eindhoven University of Technology. His interests include narrow linewidth III-V lasers and laser stabilization for fibre strain sensing and RF generation.

**Huub Ambrosius** Dr. Huub Ambrosius received his Ph.D. degree in chemistry from the Catholic University of Nijmegen (now Radboud University) in 1981. After that he joined Philips research labs in Eindhoven working on III/V technology for lasers and photodetectors. From September 1987 to September 1988 he worked as exapt at the Philips Research Lab in Limelie-Brevannes (France). After the acquisition of the Philips Optoelectronic Centre by Uniphase (later JDS Uniphase) in 1998 he was Engineering Manager in the Waferfab until 2004. In 2005 he co-founded Cedova BV in Eindhoven and in 2009 he joined the Optoelectronic Devices group at the Eindhoven University of Technology responsible for the clean room activities and the technology. Currently he is Managing Director of NanoLab@TU/e, the cleanroom facility of the Eindhoven University of Technology.

**Kevin Williams** received the B.Eng. degree in electrical engineering from the University of Sheffield, Sheffield, U.K., in 1991 and the Ph.D. degree in physics from the University of Bath, Bath, U.K., in 1995. He moved to the University of Cambridge, Cambridge, U.K., in 2001, where he was a Lecturer and Fellow at Churchill College. In 2006, he moved to COBRA Research Institute, Technical University of Eindhoven, Eindhoven, The Netherlands, with a Marie Curie Chair. His research interests include the design, realization, and demonstration of high-speed integrated photonic circuits. Dr. Williams was awarded a University Research Fellowship from the Royal Society, U.K., in 1996. He received a VICI Award from the Netherlands Organisation for Scientific Research (NWO) in 2011.

**Nicolas Michel** received the Ph.D. in Microwave and Microtechnology from the University of Lille 1, France, in 2004. Has been involved in high power diode laser engineering from 2004 to 2010 and in GaN device processing from 2010 to 2017, both at III-V Lab.

**Frederic Pommereneau** is a research engineer with the Nokia-Thales III-V Lab. He received his doctoral degree from Université de Paris XI at Orsay. He is now responsible for technology implementation including lithography and etching on III-V semiconductors.