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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 grating (AWG) laser-based transmitter consisting of eight BH-SOAs and a deep-ridge waveguide. A side-mode suppression ratio (SMSR) of up to 57 dB and a linewidth of 1.5 MHz are achieved.

Index Terms—Photonic Integrated Circuits, Generic Platform, AWG, AWGL, Buried-Heterostructure

I. INTRODUCTION

IN a generic photonic platform a large variety of photonic integrated circuits (PIC) can be realized within the same process. Different circuits, designed by different users can be fabricated even within the same wafer, sharing the cost of the infrastructure, design tool development, process development and materials costs. The designer can choose from a set of basic components, called building blocks (BBs) stored in a library [1], [2], [3]. Indium Phosphide (InP) platforms offer both active BBs (semiconductor optical amplifier, modulators and lasers) and passive BBs including arrayed waveguide gratings (AWGs) and multi-mode interference (MMIs) devices.

Low power consumption and good thermal efficiency are key aspects when designing a PIC and buried-heterostructure lasers and SOAs are attractive components as they show low threshold current [4] and good thermal behaviour as a result of the efficient heat dissipation [5], [6]. Ridge waveguide lasers and amplifiers suffer from lateral spreading of the current that limits the electrical injection efficiency and poor heat

Fig. 1: simplified schematic sketch of buried ridge stripe (a), blocking-junction (b) and semi-insulating (c) buried-heterostructure lasers

dissipation thus motivating the inclusion of BH lasers in the platform [7], [8].

In [9] we reported a finite element model, able to predict the thermal performance of BH and SR lasers, showing a reduced thermal resistance (R_{th}) of 40% in BH lasers. This is attributed to the embedding of the active layer in an InP layer that has high thermal conductivity ($68 \text{ W m}^{-1} \text{ K}^{-1}$), whereas in an SR the active region is within a continuous InGaAsP ($5 \text{ W m}^{-1} \text{ K}^{-1}$) layer and the ridge is clad with a thermally insulating polyimide ($0.1 \text{ W m}^{-1} \text{ K}^{-1}$) layer.

Three prominent configurations of BH lasers have been developed and they can be differentiated depending on how the current is laterally confined. Fig. 1 shows a simplified schematic sketch of the cross-section of buried ridge stripe (Fig. 1-a), blocking-junction (Fig. 1-b), and semi-insulating BH lasers (Fig. 1-c).

In buried ridge stripe (BRS) (Fig. 1a) a single step p-InP regrowth is used for burying the mesa. This structure consists of two n-InP/p-InP homojunctions on each side of the mesa, and one heterojunction which includes the n-InP/active-layer/p-InP stack. The switch-on voltage of the active junction is lower than the switch-on voltage of the homojunctions surrounding the mesa, ensuring that current flows through the heterojunction for the anticipated operating range. To further reduce the leakage current, proton implantation is used to make the InP highly resistive [10]. High performance BRS BH Fabry-Perot (FP) lasers have been reported showing threshold currents lower than 10 mA [11].

Blocking-junction structure lasers (Fig. 1b) require two regrowths: the first regrowth consists of a reverse biased junction. The regrowth is selective, meaning that the mask used to define the mesa is not removed during regrowth. The second regrowth is not selective and consists of the p-InP cladding and ternary layers. Charles et al. [12] demonstrated modulation of a blocking-junction FP DFB laser of 10 Gb/s up to 100°C.

In SI-BH lasers (Fig 1c) two regrowths are also needed;

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the first selective regrowth consists of a semi-insulating semi-conductor, usually Fe-doped InP. The second non-selective regrowth consists of the p-InP cladding and ternary layers. In [13], 25.8 Gbp/s direct 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 Suzuki 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: jepix.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 R_{th} , threshold current (I_{th}) and 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 core layer containing the quantum well stack and for the ternary contact layer.

is required, for example for small-radius bends (50 μ m), and for MMI-reflectors and AWGs. For the deep ridge waveguide, the etch is performed through the core layer providing the strongest optical confinement.

Shallow-Ridge (SR) waveguides (see Fig. 2b) are used when the lowest propagation losses are needed. The etching is only 100 nm into the core-layer.

The established SR SOA BB (see Fig. 2c) has the same etching depth as an SR passive waveguide, and it contains multi quantum-wells (MQWs) in the core layer to provide gain. The gain-section BB is also used to fabricate a Fabry-Perot (FP) laser when combined with reflectors to create the cavity.

In the BH SOA building block, the mesa defining the optical waveguide is first etched and then buried by an InP regrown layer which has a higher band-gap, lower refractive index and higher thermal conductivity than the core material, providing both carrier and photon confinement and efficient heat dissipation.

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

Fig. 3: Schematic representation of the process flow for Buried-Heterostructure (BH) integration in the generic platform. Step d represents the lithography necessary to integrate the BH waveguide and step h represents the implantation.

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

Fig. 4: Butt-joint between BH and ridge sections.

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 Γ 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 ΔP . By increasing the injected power, the temperature inside the active layer will also increase by ΔT 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]:

$$R_{th} = \frac{\Delta T}{\Delta P - P_{opt}} = \frac{\frac{\Delta\lambda}{\Delta T}}{\frac{\Delta P - P_{opt}}{\Delta\lambda}} = \frac{\Delta\lambda}{\frac{\Delta\lambda}{\Delta T} * (\Delta P - P_{opt})} \quad (1)$$

where P_{opt} is the emitted optical power. $\frac{\Delta\lambda}{\Delta T}$ is equal to 0.12 ± 0.01 nm. $\frac{\Delta\lambda}{\Delta T}$ 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.

Fig. 5: Measured (symbols) and simulated (dotted lines) values of thermal resistance for SR and BH lasers of different lengths.

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 ΔT 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

Fig. 6: Integrated power for BH (top) and SR (bottom) 690 μm -long FP laser at 12°C, 25°C, 35°C and 45°C.

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

Fig. 7: Threshold current density for BH and SR lasers. Characteristic temperature values of 43 K and 51 K are measured from the gradient for BH and SR lasers respectively.

Fig. 8: (a) mask layout (B) and microscope picture (b) of the 8 channel AWGL.

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.

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. 10: Fabricated chip and optical setup used for optical spectrum measurements.

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)

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

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. 13: Measured linewidth of the AWG-Laser. The Lorentzian fit gives a linewidth of 1.5 MHz.

The measured linewidth is 1.5 MHz and is found as the full width at half maximum of the Lorentzian fit of the RF spectrum. The measurement result and the fit are presented in Fig. 13.

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.

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