Abstract—The extension of a photonic integrated circuit foundry process flow is proposed by integrating selective area growth (SAG) to enable bandgap tuning for each individual active building block. The process adaptations and the impact on performance are reviewed in terms of morphology requirements and topology reduction. This platform extension enables bandgap tuning for a set of active devices to cover the wavelength range from 1453 to 1651 nm. Integration is demonstrated in combination with active-passive butt-joint technology to create the most comprehensive range of generic building blocks. Performance and limitations of the range of achievable band-edges within the same monolithic wafer are studied for amplifiers and extended cavity lasers.

Index Terms—Generic photonic integration, selective area growth, photonic integrated circuits, butt-joint integration, multi-project wafer run.

I. INTRODUCTION

MONOLITHIC InP photonic integration enables the fabrication of complex photonic circuits with active and passive devices for many applications in sensing and communication [1]. The generic platform approach gives access to a library of basic building blocks (BBs) which can be combined to make application specific photonic circuits with the same manufacturing process [2]. This approach leads to a reduction of design time and shared costs for design, fabrication and process [3]. Current InP generic technology consists in a single active section growth, which restricts the wavelengths range for active photonic devices to a few tens of nanometers.

The range of wavelengths available within one circuit can be greatly extended by using a technique called selective area growth (SAG). A dielectric hard mask pattern is defined prior to the epitaxy to locally enhance the growth rate of multiple quantum wells (MQW). As a result, the MQW thickness is increased and the bandgap is tuned. The growth mechanisms in the presence of a dielectric mask has been studied in detail [4], [5], [6], [7]. High performance photonic integrated circuits (PICs) with multi-bandgap integration are enabled by the SAG technique [8], [9]. Recently, a 10 channels WDM transmitter on a single chip has been demonstrated over an 80 nm-wide wavelength range provided by a single epitaxial step and integration with passive devices [10]. SAG also has been integrated in a photonic platform to fabricate a DFB laser array over a 155 nm wavelength range [11]. However, to the best of our knowledge, SAG has not been integrated with the full library of building blocks offered in a comprehensive PIC platform. Integrating SAG into a generic platform enables bandgap tuning for all the active building blocks including detectors, modulators and lasers which can be combined with passive filters, combiners and mode size adaptors which are already defined in the generic platform.

A number of challenges have to be addressed to co-integrate selective area growth with the generic platform. First, the growth conditions have to be adapted to a layer stack compatible with the building blocks of the platform. Second, the butt-joint regrowth of the passive layer stack should provide defect-free interface regardless of the thickness variations induced by SAG. Third, the topology induced by SAG on the wafer has to be reduced to be compatible with the generic fabrication process.

This paper presents the process development to integrate SAG in full compatibility with the generic platform. This enabled the fabrication of the first SAG-generic MPW run and allowed device characterization as a function of bandgap tuning. The fabrication of multi-section semiconductor optical amplifiers (SOAs) enabled measurement of modal gain variations with SAG by using a method recently developed with the platform BBs [12]. Extended cavity Fabry–Pérot lasers were also measured to evaluate their performance across the bandgap range available on the wafer. All processing steps until the active layer stack SAG were made at III-V Lab, and the butt-joint regrowth followed by the generic process flow described in [2] was carried on at the TU/e.

The paper is organized as follow. Section II describes the adaption of SAG technology to provide an active layer stack compatible with the generic technology. In section III, we present the validation of the butt-joint technology to integrate SAG active devices with generic passive devices. Section IV describes the reduction of topological variations obtained with etch-stop layers. Section V presents the fabrication of a SAG-generic MPW run and the characterization of the influence of SAG on device performance through microphotoluminescence, gain and extended Fabry–Pérot lasers measurements. Finally, a summary and conclusion of this work is
made in section VI.

II. SELECTIVE AREA GROWTH COMPATIBLE WITH THE GENERIC TECHNOLOGY

The generic platform used in this work is based on an active-passive butt-joint integration. Therefore comparable effective refractive indexes for the two layer stacks are required to minimize reflections at their interface. The passive layer stack of the platform contains a 500 nm-thick core layer to provide low-loss waveguides. As a consequence, the active layer stack has to contain thick layers in addition to the MQW structure. Previous work has shown that SAG induces strain variations next to the mask [13]. In case of thick layers, a strain build-up can cause crystallographic defects to propagate through the layer stack. Therefore a study of the growth morphology and the growth condition is necessary in order to reduce the strain build-up into thick layers and provide a defect-free active structure in presence of SAG masks.

A. Experimental growth conditions

Prior to the growth of the active layer stack, pairs of dielectric (SiO₂) mask stripes (referred to as the SAG mask) are defined on the wafer. Fig. 1 shows the schematic top view of an SAG mask and its design parameters. The opening between the mask stripes is chosen to be 20 µm to provide a trade-off between low device footprint and lithography alignment tolerance (also known as mask overlay error) with subsequent masks. The presence of the dielectric mask provides a growth rate enhancement (GRE) in the central opening, increasing the quantum wells thickness and therefore decreasing their bandgap energy [13].

The active layer stack used in this work consists of an n-doped InP buffer layer, a waveguide core with AlInGaAs MQW embedded within InGaAsP separate confinement heterostructures (SCH) and a p-doped InP cladding layer. To minimize the reflections at the active-passive interface, the active layer stack far from the SAG masks (referred to as the field area) contains a 360 nm-thick waveguide core with an 80 nm-thick MQW structure in its center. This layer stack results in 140 nm-thick SCH layers around the MQW.

B. Growth conditions adaptation

A study of growth conditions was carried out to characterize the consequence of strain build-up into thick SCH layers. Table I summarizes the growth condition variations and the linear density of defects observed between the SAG mask stripes for reference SAG mask widths of 25 µm and 50 µm.

A first growth was made at 150 mbar to characterize the consequences of strain build-up with conditions comparable to previous results [7]. A second growth was performed with SCH thickness of 20 nm to evaluate the morphology in case of thin SCH layers. Subsequently, three growth condition adaptations were performed one after another to study the compatibility of SAG with the designed active layer stack. In growth number 3, the SCH are grown with a slight tensile strain of 500 ppm (0.05%) in the field area. This aims at compensating the composition variation towards compressive strain next to the SAG masks. In addition to the tensile strain, a reduced pressure is used for growth 4 to increase the vapor-phase diffusion coefficient of gas precursors and attenuate the effect of the SAG mask [14]. Finally, the growth 5 is made in the same conditions as growth 4 with reduced precursors gas flow to divide the growth rate by 4 (referred to as R/4). This decrease of growth rate modifies the growth mechanisms at the mask edge and reduces the overgrowth [15], [16]. All the epitaxial growths were performed by metal-organic vapor phase epitaxy (MOVPE) at 650 °C. Trimethyl-metal gas precursors were used as a source for group III elements, and arsine and phosphine gas were used for group V elements.

This set of experiments enables the study of the influence of growth conditions on morphological defects in presence of SAG mask. Using thin SCH layers for growth 2 indicates whether the morphological defects observed in growth 1 are related to their thickness. The addition of tensile strain, reduction of growth pressure and reduction of growth rate for growths 3, 4 and 5 show which growth conditions are suitable to prevent strain build-up into the active layer stack.

The first growth lead to crystallographic defects propagation across active layers for a 25 µm-wide SAG mask. In contrast, the second growth with thin SCH layers showed no defect with the same SAG mask width, and only residual defects were visible for a 50 µm-wide SAG mask. The third growth with tensile strain provided a reduction of linear density of defects by 33 % compared to the growth 1. The fourth growth at reduced pressure provided a defect-free morphology for a 25 µm-wide mask. Nevertheless, small defects were still remaining in the case of large masks of 50 µm width. The fifth growth at reduced growth rate also showed no defect for a 25 µm-wide mask, but did not lead to a reduction of defect density for 50 µm-wide SAG mask.

The result of the 2 first growths confirms that when growing thick SCH layers, special care regarding the growth conditions is needed to prevent the formation of morphological defects.
Adding a tensile strain and reducing the growth pressure lead to defect-free growth for a 25 µm-wide SAG mask. The residual defects present for 50 µm-wide SAG masks indicate that an effect other than over-strained SCH appears to be problematic with such strong growth rate enhancement.

A microscope picture of a detail of SAG mask stripes after the growth 1 is shown in Fig. 2 a). Morphological defects are visible across the active stack between the two mask stripes. As a comparison, Fig. 2 b) shows a microscope picture of a 33 µm-wide SAG mask after the growth 5 combining strain compensation, reduced pressure and reduced growth rate. In this case, there is no defect propagation across the SAG mask opening.

The absence of morphological defects for SAG masks up to 33 µm (as shown in Fig. 2 b)) provides a large range of possible bandgaps for a layer stack compatible with the generic platform. The active layer stacks presented in the rest of this paper were grown with the same conditions as growth 5 in Table I.

### III. SELECTIVE AREA GROWTH AND BUTT-JOINT INTEGRATION

The butt-joint integration is combined with the SAG technique by designing the active areas between the two SAG mask stripes, as depicted in Fig. 3. A 10 µm-wide active stripe is designed in the center of the 20 µm opening between the SAG mask stripes. The remaining design area is available for passive devices. A 2 µm-wide waveguide is designed in the center of the active layout, where the MQW composition provided by SAG is constant. Schematics of the cross-section along the waveguide direction during the main processing steps of the passive butt-joint regrowth are shown in Fig. 4. After growing the active layer stack, step 1 (Fig. 4 a)) consists in covering areas to be kept active with a SiNx hard mask. In step 2 (Fig. 4 b)), the uncovered part of the active layer stack is wet etched. Then, the regrowth of a passive layer stack around the active area is made in step 3 (Fig. 4 c)). After wet etching the active area mask, the contact layer growth is performed in step 4 (Fig. 4 d)) by depositing an InP layer with graded p-doping and a p++ InGaAs layer. The butt-joint regrowth and the contact growth are done in an MOVPE reactor at 650 °C and 100 mbar. In the same way as during the active stack growth, trimethyl-metal, arsine and phosphine gas are used.

The standard active layer stack in the generic platform contains a 500 µm-thick InGaAsP core to match the passive waveguide core thickness. Fig. 5 a) shows the cross-section of a butt-joint interface obtained in the platform along the waveguide direction. In case of SAG, the thickness of the active core layers vary between 360 nm and 460 nm. This thickness difference influences the conditions for passive regrowth for different active devices. Therefore, characterizing the active-passive interface quality for the different active layer stack thicknesses is necessary.

Active-passive interfaces with different SAG widths have been designed on the wafer to characterize the influence of active stack thickness on the butt-joint process. After the fabrication of the wafer, cuts along the waveguide direction at the butt-joint location have been performed with focused ion beam. Scanning electron microscope (SEM) pictures of the cut butt-joint interfaces were taken to observe the regrowth morphology. Fig. 5 b) shows a butt-joint interface obtained in the field area and Fig. 5 c) shows a butt-joint interface obtained in the center of a 35 µm-wide SAG mask. The absence of SAG mask in the field area provides the thinnest active layer stack and the 35 µm-wide SAG mask provides the thickest layer stack used for active photonic devices. For both 360
and 460 nm-thick active core layers, the passive layer stack grown is flat, the active-passive interface is completely filled with material and the overgrowth of the passive core is low. The morphology of the butt-joints with SAG in Fig. 5b) and Fig. 5c) are of the same quality as the one obtained with a 500 µm-thick core layer of the platform (Fig. 5a)), thus showing the success of the butt-joint regrowth with the generic passive layer stack for different active stack thicknesses provided by SAG.

IV. REDUCTION OF SAG TOPOLOGY

The selective growth of the active layer stack induces topologies of hundreds of nanometers at the surface of the wafer. Such a step height can induce inhomogeneities in the resist layer and degrade the waveguide lithography used in the generic process. This topology is present for two reasons: first, the absence of growth on the dielectric mask creates a step as high as the layer stack thickness. Second, after removing the SAG mask, the wet etch of the active layer stack also etches the InP substrate where the active stack was not grown. Therefore large topologies can be created at these locations.

To reduce the etch depth into the InP substrate, two etch stop layers have been grown below the active layer stack. By studying the selectivity of InP and InGaAsP layers during wet etching, a stack of two 10 nm-thick InGaAsP etch stop layers separated by a 80 nm-thick InP layer were designed to minimize the etch depth and provide a tolerance for possible etch depth variation across the wafer.

Fig. 6a), b), c) and d) show schematic cross-sections in the direction perpendicular to an active stripe for the 4 main steps of the butt-joint and contact layer growth process described in section III. Fig. 6e), f), g) and h) show profilometer measurements performed during the wafer fabrication for the same process steps. These measurements give access to the step height and allow the characterization of the influence of the etch stop layers. The case of 35 µm-wide SAG mask is shown as it provides the highest topology for active devices on the wafer.

The initial step in Fig. 6a) and e) shows the profile after the growth of the active stack, the wet etch of the SAG mask, and the deposition of the hard mask for the active area. The step height corresponds to the total active layer stack thickness with growth rate enhancement (780 nm in case of a 35 µm-wide SAG mask). During the wet etch of the active layer stack (Fig. 6b) and f)), the two etch stop layers limit the etch depth in the substrate to 270 nm. Then, this step height is transferred during passive regrowth (Fig. 6c) and g)) and an additional overgrowth of 50 nm occurs at the edges of the active area mask. Therefore a 320 nm total height difference occurs at the edges of the active area mask. The final topology obtained makes it possible to proceed with the generic fabrication process.
V. SAG-Generic Fabrication and Characterization

The technological developments described above enabled the fabrication of a number of active-passive PICs in the first SAG-generic MPW run. Test cells made it possible to perform measurements across the available range of SAG mask widths. The photoluminescence peak wavelengths provided by bandgap tuning, the net modal gain of active sections and the performance of extended cavity Fabry–Pérot lasers are described in this section.

A. Multi project wafer run

A full MPW run was implemented with the process modifications described in sections II and IV. Only the active BBs were modified to add the SAG mask for bandgap tuning, and only one extra mask is necessary for the definition of the SAG mask pattern prior to the active layer stack growth. After this growth and the wet etch of the SAG dielectric mask, the rest of the generic fabrication process was performed as described in [2]. Fig. 7 shows a photograph of a 51 mm (2-inch) wafer after metal deposition and lift-off.

The integration of SAG with minimal design and processing modifications gave access to all active and passive BBs from the platform process design kit with marginal design rule modification. Two application specific cells and 9 test cells were fabricated on the same wafer. The performance of two application specific PICs on the same MPW wafer were recently shown for a tunable laser source [17] and broadband light emitting diode [18].

B. Micro-Photoluminescence

To characterize the available wavelength range for active devices on the wafer, micro-photoluminescence (µ-PL) measurements have been performed. A laser beam was focused with a 3 µm spot size in the center of SAG mask openings to measure the emission where the active waveguides are designed. The µ-PL peak wavelength as a function of SAG mask width is presented in Fig. 8. SAG mask widths from 0 (meaning absence of SAG mask) to 35 µm provided a wavelength range from 1453 to 1651 nm, comparable to previous work aiming at a wide wavelength range [19]. The wide range of wavelengths provided shows that SAG can be implemented with the passive layer stack designed for generic integration.

C. Gain measurements

A multi-section amplifier method for gain spectrum characterization is implemented [12]. Multi-section SOA devices shown schematically in Fig. 9 are used for gain measurement. They consists in five 150 µm-long SOAs separated by 30 µm-long passive sections partially etched to provide electrical isolation. An array of such multi-section SOA devices has been fabricated using a range of SAG mask widths to enable the characterization of the gain as a function of growth rate enhancement. To record the amplified spontaneous emission (ASE) spectra, the chip was placed on a copper holder kept at a constant temperature of 20 °C with a TEC unit. Four electrical probes were used to inject current into the SOAs. The output power was collected by a lensed optical fiber. A 10:90 splitter was used to direct 10 % of the light into a power meter for fiber alignment control and 90 % to an optical spectrum analyzer (OSA) to record the output spectrum. With different biasing configurations, the total SOA length under current injection was adjusted to be 150, 300, 450 and 600 µm. For each configuration, the ASE spectrum was recorded from the same output waveguide. A four points fitting was performed on the measured emission from the four equivalent SOA lengths to extract the modal gain spectra, as described in [12]. Gain spectra were measured for current densities from 1.5 to 10 kA.cm$^{-2}$. Fig. 10 shows the gain spectra extracted for the highest current injection measured for SAG mask widths ranging from 0 to 31 µm.

Peak gain values above 30 cm$^{-1}$ are obtained over a 210 nm range. The evolution of the gain with the SAG mask width
shows a first increase of gain peak for wavelengths from 1456 to 1573 nm, optimum gain peak values up to 72 cm$^{-1}$ from 1573 and 1635 nm, and a decrease of the gain for structures with longer peak wavelengths. Gain peak values around 70 cm$^{-1}$ at 10 kA.cm$^{-2}$ are similar to the values obtained in the generic platform without SAG [12], [3]. The variation of gain as a function of SAG mask width is assumed to be due to the variation of the MQW structure. Thickness and composition variations induced by SAG have influence over the MQW performance.

**D. Fabry–Pérot Lasers**

The performance of the SAG-generic integration in the platform is assessed through the characterization of arrays of extended cavity Fabry–Pérot (FP) lasers with different SAG mask widths. The laser structure is presented in Fig. 11. It consists in a 500 μm-long gain section connected to passive waveguides on each side to form an extended 4.6 mm-long cavity. As-cleaved facets provide 33 % reflection. Gain sections with 10 different SAG mask widths from 0 to 36 μm were designed to study the variation of lasing performance with bandgap tuning.

To measure the light-output versus current (LI) characteristics of the lasers, the chip was placed on a copper holder kept at a constant temperature of 20 °C with a TEC unit. The lasers were probed and driven in continuous wave regime and the output light from one facet was collected with a large area photodetector. The measured LI characteristics for a range of SAG mask widths is presented in Fig. 12. Eight lasers with SAG mask widths up to 27 μm show output powers from 5.7 to 10.5 mW at 200 mA current injection. The two lasers with threshold exceeding 50 mA correspond to SAG mask widths of 31 and 36 μm. Fig. 13 summarizes the threshold current and slope efficiency obtained for the set of lasers as a function of SAG mask width. The threshold current of each laser was extracted by identifying the peak of second derivative of the LI characteristic. The slope efficiency is measured from a linear fit of the LI characteristic over 10 mA above threshold. The threshold currents show limited variations from 35 to 41 mA for SAG mask widths from 0 to 27 μm. For wider SAG masks, a sharp increase of threshold current occurs up to 140 mA for a 36 μm-wide mask. The slope efficiency at threshold is stable over a SAG mask range from 0 to 15 μm with values from 80 to 100 mW/A, and then show a progressive decrease for wider SAG masks.

Measured spectra for the extended-cavity FP lasers are presented in Fig. 14. The current injection used was 100 mA for the first 9 lasers and 180 mA for the laser with 36 μm-wide SAG mask. The spectra were recorded at 20 °C by coupling the output light from one facet to a optical fiber, introducing a coupling loss estimated at 3 dB. A 10:90 splitter was used to direct 10 % of the light into a power meter to control the fiber alignment and 90 % to an OSA to record the output spectrum. The lower output power recorded from the laser with 9 μm-wide SAG mask is attributed to damage of the device during handling. Lasing operation over a 254 nm wavelength range (1470–1724 nm) is demonstrated.
Fig. 13: Threshold current (red squares) and one side slope efficiency (blue dots) of Fabry–Pérot lasers measured as a function of SAG mask widths.

Fig. 14: Spectra of Fabry–Pérot lasers for different SAG mask widths. The power density was recorded in fiber from one side of the laser with a 0.5 nm resolution bandwidth (RBW). The current injection was 100 mA for the first 9 lasers and 180 mA for the laser with 36 µm-wide SAG mask.

VI. CONCLUSION

We demonstrated the integration of SAG and generic foundry technologies using a butt-joint process. An adaptation of the growth conditions enabled a defect-free SAG growth morphology with 140 nm-thick SCH layers in the field area. A defect-free butt-joint interface has been shown for the case of absence of SAG mask and for the case of a 35 µm-wide SAG mask, confirming the compatibility of the SAG technique with the generic process. The design of etch stop layers combined with the butt-joint integration allowed the reduction of topologies on the wafer from 780 nm to 320 nm, which enables the use of a mature generic fabrication process.

For the first time an SAG-based MPW run was fabricated with minimal design modifications from the standard technology. A wide wavelength range of 200 nm has been obtained from measurements of peak PL intensities with SAG mask widths ranging from 0 to 35 µm. Direct gain measurements were performed with standard test structures in the platform across the bandgap range provided by SAG. Peak modal gain values above 30 cm\(^{-1}\) are recorded over a 210 nm range, with a maximum value of 72 cm\(^{-1}\), comparable to the mature generic technology. Extended cavity FP lasers have been fabricated over the available range of bandgaps to characterize the potential of SAG for active devices. Threshold currents as low as 35 mA with corresponding slope efficiency of 97 mW/A are reported with SAG mask width of 15 µm. Limits in device performances are shown with SAG mask widths above 27 µm. This work represent the first successful integration of SAG technology into a generic foundry platform. It opens the possibility to use the full generic platform capability with bandgap choice for each active building block.

REFERENCES


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