Laser Array Covering 155 nm Wide Spectral Band Achieved by Selective Area Growth on Silicon Wafer

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Abstract *Vertical p-i-n AlGaInAs lasers obtained from a single Selective Area Growth (SAG) step on a thin InP layer bonded to silicon wafers are presented. A PL extension from 1490 nm to 1645 nm was demonstrated on InP-SOI wafer. Based on this result, a record of 155 nm wide spectral range was obtained for FP lasers on InP-SiO_2/Si wafer.*

Introduction

Coarse Wavelength Division Multiplexing Systems (CWDM) are largely encouraged by the increasing demand for higher capacity optical networks[1]. However, the « Photonic Moore's law » implies that although datarates increase, power consumption and costs should remain stable over time[2]. The silicon photonics platform is of particular interest to enable low-cost large-scale fabrication of PICs considering the maturity of CMOS-technology. Plus, it offers various optical functions such as passive waveguides, (de)multiplexing functionnalities and efficient modulators[3]. However, the integration of III-V semiconductors onto Si wafers is mandatory to fabricate efficient light sources. III-V on Si heterogeneous integration through wafer-bonding allows for dense and wafer-scale integration of the III-V optoelectronic components in the silicon photonic platform[4].

CWDM are particularly adapted to reduce power consumption thanks to uncooled operation due to the large inter-channel wavelength shift of 20 nm between the laser array. For a 8-channels CWDM, there is a need for at least 140 nm-wide photoluminescence (PL) extension between the 1st and the 8th laser in the array. With respect to a more a traditional approach, based on discrete DFB lasers fabricated from different epitaxial growths and then integrated onto a SOI wafer using die-bonding[5], Selective Area Growth (SAG) allows to obtain the entire set of emission wavelengths with a single epitaxial growth onto a wafer[6]. A pair of selective mask patterns made from silica 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. High performance photonic integrated circuits (PICs) with multi-bandgap integration are enabled by the SAG technique on InP substrate[7][8][9].

Recently, to extend the mature building-blocks from the InP platform into the III-V/Si hybrid platform, a new integration platform based on wafer-bonding and regrowth techniques is being developed[10][11]. Following this approach, we have recently demonstrated that a 3 µm-thick laser structure grown on InP-SiO_2/Si (InPoSi) substrate shows laser performance similar to the ones obtained for the same structure grown on InP substrate[12]. This thickness has been achieved despite the thermal strain induced by the difference of thermal coefficient (CTE) between InP and Si[13][14]. In this paper, we propose a novel SAG process to integrate a multi-λ laser array onto silicon based on a single growth step of a 3 µm-thick vertical p-i-n laser structure.

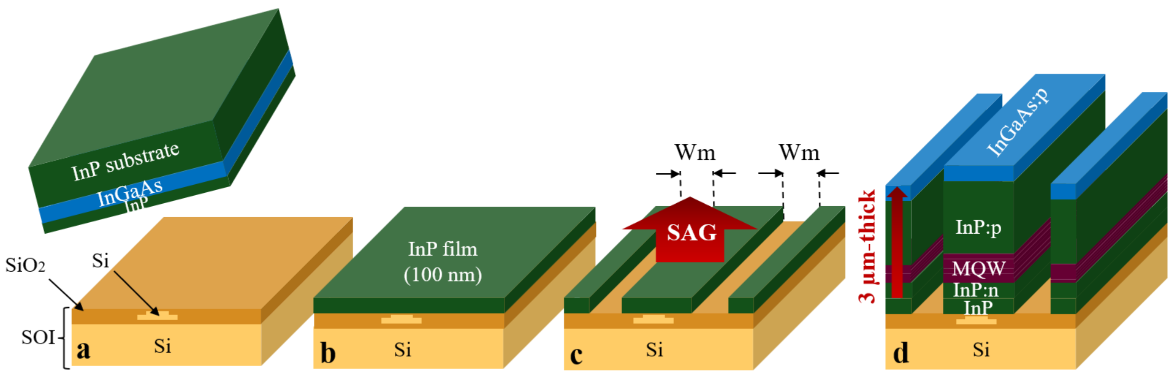

Figure 1 Fabrication process for the integration of multi-λ laser array on SOI wafer: (a) Direct-bonding of a III-V stack previously grown onto an InP substrat onto a processed SOI wafer; (b) Removal of the InP substrate and the InGaAs sacrificial layers; (c) Etching of the InP layer to form the masks for SAG; (d) SAG of a 3 µm-thick laser structure.

Selective Area Growth (SAG) material evaluation on InP-SOI wafer

The fabrication process is described in Figure 1. First, the InP-SOI substrate was fabricated by means of an epitaxial growth step of an InGaAs sacrificial layer followed by an InP bonding layer on a 2-inch InP substrate. In the meantime, a SOI wafer was fabricated at CEA-LETI's 200 mm line[15]. The fabrication relies on a standard process using a 200 mm SOI wafers with a 500 nm-thick silicon top layer. Passive rib waveguides were formed by etching the silicon layer. These waveguides are optimized for the coupling with III–V waveguides aligned on top of the silicon waveguides. For the passive circuitry, additional etching steps were applied to form both 300 nm thick strip and rib waveguides and other passive elements such as vertical output couplers. To planarize the surface of the SOI wafer, a silica layer is deposited and a chemical-mechanical polishing is applied. Then, the III-V structure was bonded at room temperature to the SOI wafer and heated up to 300 °C for 2 hours following conventional hydrophilic direct bonding process[16] (Figure 1a). After that, the InP substrate as well as the InGaAs sacrificial layers were selectively removed by chemical etching (Figure 1b). The InP-SOI substrate was resized to 3-inch in order to fit the dimension of our MOVPE growth equipment. Finally, a new SAG process was specifically developed on InP-SOI. To do so, the silica from the SOI wafer was locally digged out by the etching of the InP layer in order to open the variable-sized dielectric surfaces for the SAG process (Figure 1c). By adjusting the width of the opening (W_m), the thickness of the MQW structure, therefore its photoluminescence emission, can be tuned. We used mask's width W_m of ranging from 5 µm ($W_{m,i}$) to 30 µm ($W_{m,n}$) by step of 5 µm, while the distance between the masks was set to be 30 µm. Our SAG process enables the growth of the 3 µm-thick laser structure. The latter is composed of a n-contact layer made of InP, an active structure composed of AlGaInAs-based MQWs, a InP:p cladding and a p-contact layer made of InGaAs (Figure 1d).

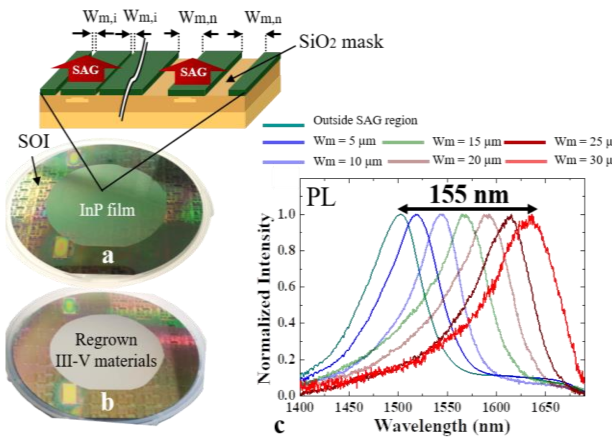

Figure 2 SAG applied on InP-SOI wafer: (a) Before growth (b) after SAG; (c) PL spectra obtained in the different SAG regions.

The InP-SOI wafer is presented in Figure 2a. After SAG, the polycristalline deposition onto the SOI part was cleaned by chemical etching (Figure 2b). The PL signals of the different regions obtained by SAG are presented in Figure 1c. They were measured by means of a system equipped with a µ-source excitation laser at 1064 nm and an InGaAs detector. A 155 nm-wide wavelength range from 1490 nm to 1645 nm was successfully obtained, which demonstrates that our SAG process can be applied on InP-SOI wafers. The full width at half maximum (FWHM) of the PL signals is almost constant over the entire spectral range. The latter is a clear signature of high-crystal quality of the MQW for the different SAG regions. A significantly lower signal-to-noise ratio is measured for the PL peaks at 1650 nm because of the limited responsivity of the InGaAs detector of our PL setup for wavelengths above 1600 nm.

Device Fabrication on InPoSi wafer

The benefit from SAG on InP-SOI wafer can be fully exploited if only the design of all the passive functions (waveguide dimensions, vertical output coupler...) is optimized to cover a broad spectral range. Significant effort is currently being deploied in order to optimize the wavelength dependent behavior of our key passive building blocks on SOI. In this work, in order to evaluate the performance of SAG based active regions, we have focused on laser test vehicules which are not affected by the influence of the passive functions onto the optical mode. To do so, we have fabricated FP laser array from III-V laser structures selectively grown onto an InP layer bonded onto InPoSi. The latter consists of a thermally oxidized silicon wafer containing a 200 nm-thick silica layer at the bonding interface where the InP bonded layer was locally etched for the SAG process. This configuration enables the evaluation of the laser performance without any influence of the passive functions from the SOI wafer. Shallow-ridge laser structures have been fabricated using the process developed in our platform[17]. Then, 500 µm-long bars containing all the lasers have been cleaved (a) and soldered on thermally conductive submounts. A facet of a laser has been observed by Scanning Electron Microscopy (Figure 3b). The III-V waveguide top section is 2.4 µm-large.

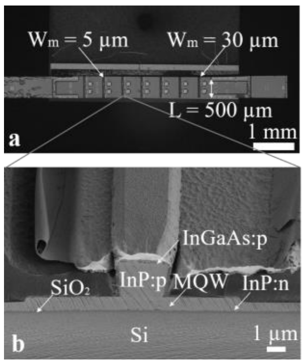

Figure 3 500 µm-long bar containing all the lasers obtained by SAG on InPoSi: (a) Microscopic image of the bar; (b) SEM image of the shallow-ridge laser structure.

Devices characteristics

Laser performance were measured by coupling through a single facet. The emission spectra of five Fabry-Pérot lasers, based on five different selectively grown MQW active regions, are presented in Figure 4. The measurements were performed at 20°C for 100 mA gain medium bias current and the emitted signals were coupled by a standard lensed optical fiber to an optical spectrum analyzer. Laser peak emission covering a 155 nm-wide range, from 1515 nm to 1670 nm for continuous-wave (CW) operation, is observed. The spectral range achieved by SAG is more than four times wider than what have been demonstrated by other groups using selectively grown AlGaInAs MQWs DFB lasers on InP-on-insulator in the O-band[10].

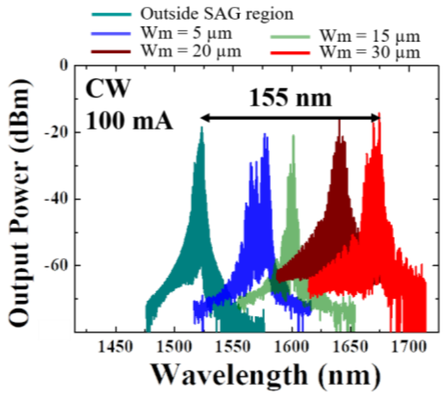

Figure 4 Spectra measured under C-W operation for a driving current of 100 mA at 20°C for the 500 µm-long lasers obtained by SAG on InPoSi.

The L-I characteristics measured using a broad-area detector in continuous-wave (CW) operation are presented in Figure for setup temperatures varying from 20°C to 70°C. The 3 µm-thick vertical p-i-n laser diode design enables to reach high power operation as opposed to thin lateral p-i-n structures[10].

A maximum output power of 20 mW for a 200 mA driving current was demonstrated for the laser emitting at 1515 nm. The laser characteristic temperature T_0[18], determined from a linear fitting of the logarithm of the current density evolution against temperature, is 69°C for the three lasers. This result shows that these three SAG defined MQW active regions have similar material properties. Moreover, due to the favorable band offsets in AlGaInAs QW as compared to InGaAsP QW[19], we obtain a high characteristic temperature, which makes this material suitable for data-center applications, for which high temperature operation is a key requirement.

Threshold currents are slightly higher for the laser emitting at 1610 nm as compared to the laser emitting at 1515 nm. The latter is due to active region design limitation which was optimized for an emission at the center of the C-band. Based on further optimization of the MQW design in this spectral range, laser performance could be improved.

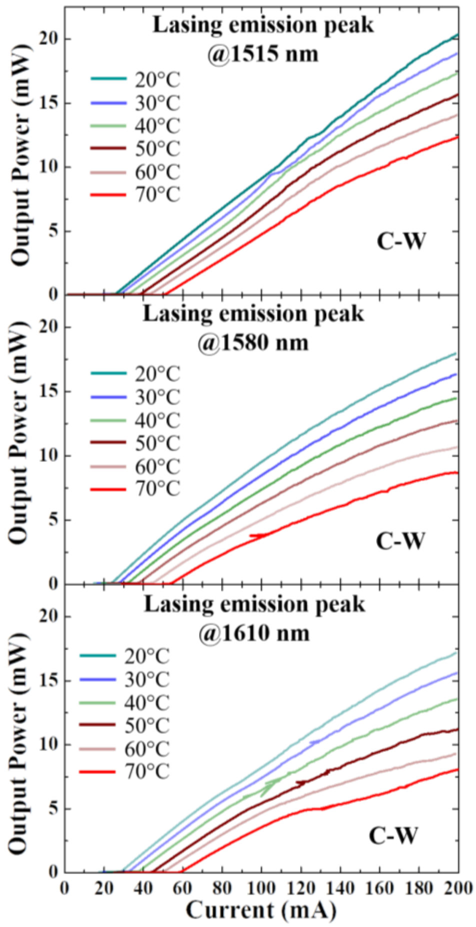

Figure 5 L-I characteristics under C-W operation for different temperatures for the lasers emitting at 1515 nm, 1580 nm and 1635 nm.

Conclusion

Single-step SAG process was developped on InP-SOI wafers enabling the growth of 3 µm-thick laser structures covering a PL extension ranging from 1490 nm to 1650 nm. Based on this technology, FP laser array were fabricated on InPoSi, to test laser performance without any influence of the passive functions on the optical mode. A 155 nm-wide spectral range from 1515 nm to 1670 nm was obtained. High power operation under C-W operation was demonstrated with a maximum of 20 mW for a 200 mA driving current. High thermal stability was shown up to 70°C for the lasers emitting from 1515 nm to 1610 nm. These results strongly emphasize that the SAG applied on InP-SOI wafer is a promising approach to fabricate laser array covering a very large spectral range, compatible with the full potential of coupling light through Si waveguides.

Acknowledgments

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