Heterogeneous III-V/Silicon-on-Insulator Photonic Integrated Circuits

G. Roelkens[1], L. Liu[1], J. Van Campenhout[1*], J. Brouckaert[1], D. Van Thourhout[1], R. Baets[1]

1 : Photonics Research Group, Department of Information Technology (INTEC), Ghent University– IMEC, St-Pietersnieuwstraat 41, 9000 Ghent, Belgium

1* *current affiliation* - IBM T.J. Watson Research Center, 1101 Kitchawan Rd., Yorktown Heights, NY 10598, USA

Abstract: III-V/Silicon-on-insulator photonics comprises the heterogeneous integration of a III-V layer on top of an SOI waveguide circuit. We elaborate on the fabrication technology and the realization of III-V/SOI photonic integrated circuits.

Keywords: Silicon Photonics, Heterogeneous integration

Introduction

Photonic integrated circuits (PICs) offer the potential of realizing low-cost and compact optical functions. Silicon-on-insulator (SOI) is an emerging material platform for this integration, due to the large omni-directional refractive index contrast that can be achieved. Moreover, the massive CMOS processing infrastructure can be used to process these optical components. However, the integration of light emitters and optical amplifiers at telecommunication wavelengths, particularly basic components to realize switching, is hampered by the indirect band gap of silicon. As this is a rather fundamental issue, this function still requires the use of III-V semiconductor materials.

In this paper we propose the integration of a III-V layer on top of an SOI waveguide circuit by means of DVS-BCB adhesive die-to-wafer bonding, to realize these active optical functions. The paper is organized as follows, in section 2 we will outline the bonding technology used for the heterogeneous integration. In section 3, the realization of III-V microdisk lasers integrated on and coupled to an SOI waveguide circuit will be discussed, while in section 4, a new type of hybrid III-V/SOI microcavity will be proposed.

2. DVS-BCB die-to-wafer bonding technology

The heterogeneous integration of a III-V layer onto an SOI waveguide circuit can be achieved by adhesive bonding using DVS-BCB. As ultra-thin bonding layers are typically required (in the order of 100nm), the cleanliness of the III-V surface and the SOI surface are of paramount importance to achieve a high-quality bond. Especially the presence of particles at the bonding interface needs to be avoided, as this would result in large unbonded areas. The cleaning of both the III-V die surface and the SOI wafer surface was optimized in order to remove pinned particles from the bonding interface. On the SOI wafer surface, a Standard Clean 1 solution ($1NH_3$:$4H_2O_2$:$20H_2O$ at 70C) is used to lift off particles. On the III-V die, the removal of a sacrificial InP/InGaAs layer pair resulted in particle and contamination free surfaces. The DVS-BCB layer is spin-coated afterwards onto the SOI waveguide circuit and is pre-cured in order to evaporate the solvents. After the pre-cure, the III-V die is attached, epitaxial layers downwards, to the SOI and the III-V/SOI stack is cured at 250C. After bonding, the InP growth substrate is removed using a combination of mechanical grinding and chemical etching using HCl, until an etch stop layer is reached. This leaves a thin III-V epitaxial layer attached to the SOI waveguide circuit, into which the opto-electronic components can be fabricated, lithographically aligned to the underlying SOI waveguide circuit [1].

3. III-V microdisk lasers integrated on SOI integrated circuits

A first example of the bonding technology outlined in the previous section is the realization of a DVS-BCB bonded III-V microdisk laser integrated on an SOI waveguide circuit. The device layout is shown in the inset of figure 1. The lasing mode is a whispering gallery mode propagating at the rim of III-V microdisk and the coupling to the underlying SOI waveguide circuit is achieved by evanescent coupling. The devices were optically pumped and continuous wave room temperature lasing was demonstrated, with up to 1uW of optical power coupled to the SOI waveguide layer. The DVS-BCB bonding layer thickness was 260nm in this case. We also proposed the concept of using an electrically injected III-V microdisk laser to generate light on the silicon platform. Although the demonstrated electrically injected devices were based on molecular die-to-wafer bonding, a DVS-BCB bonded microdisk laser is also feasible [2].

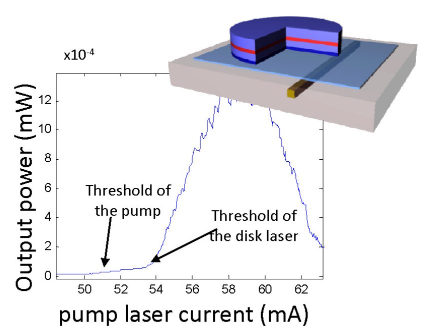

Figure 1 : DVS-BCB bonded microdisk laser bonded to an SOI waveguide circuit: continuous wave operation under optical pumping

Besides for its use as a continuous wave light source on a silicon-on-insulator photonic integrated circuit, this microlaser is also a building block for more complex signal processing functions like wavelength conversion, switching,... In this paper, we propose an all-optical wavelength converter. The principle relies on the injection locking of the DC-biased, III-V micro-disk laser. When the external control laser, carrying the data signal to be wavelength converted, is on, the injected photons will couple into the micro-disk cavity, and the number of photons of the dominant lasing wavelength will decrease correspondingly. The detected power is low in this case. While the control laser is off, the microdisk laser is lasing normally. Thus, the signal carried on the external control laser will be inversely transferred to the dominant lasing wavelength of the microdisk laser. The static measurement results are shown in figure 2. Wavelength conversion up to 5Gbit/s was demonstrated. Other than the popular pump and probe scheme, no probe beam is needed in this configuration. The converted signal is the intrinsic lasing beam from the microdisk laser. Wavelength conversion with a control power as low as several micro-watts is achieved.

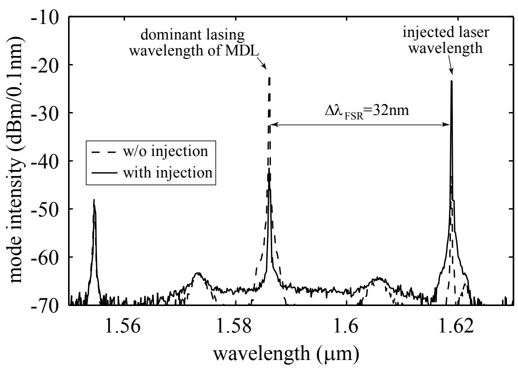

Figure 2 : Static measurement results on the injection locking of a heterogeneously integrated III-V microdisk laser on SOI

4. Hybrid III-V/SOI microcavities

In the previous section, the microdisk cavity was formed in the bonded III-V layer. This puts stringent requirements on the III-V processing quality in order to obtain a high quality factor resonator. Inspired by the work by Intel/UCSB on the hybrid laser [3], the III-V layer bonded on the SOI waveguide structure can become a part of a silicon photonic component instead of being a standalone device. As in this work nanophotonic SOI waveguide circuits are used, much denser integration can be achieved compared to the rib SOI waveguide structures used in [3]. As an example of this device configuration, in figure 3 we show an SOI racetrack resonator notch filter, onto which an 80nm thin III-V layer is bonded, consisting of an active layer structure with an emission wavelength around 1550nm. In these structures the mode is predominantly confined in the SOI waveguide layer, while the tails of the optical mode overlap with the III-V overlay. This device configuration makes the III-V post-processing very straight forward and possibly CMOS compatible. By locating the cavity in the SOI, one can also benefit from the high-resolution deep UV lithography to define the SOI cavity. Due to the high optical confinement in the SOI waveguide layer, the DVS-BCB bonding layer has to be about 50nm, in order to obtain sufficient overlap with the III-V overlay. These III-V/SOI cavities show strong nonlinear behaviour, due to the absorption that takes place in the

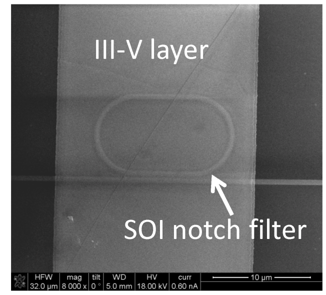

Figure 3 : SEM top view of a hybrid III-V/SOI microcavity

active layers when using a wavelength shorter than the bandgap wavelength of the III-V active layers. This absorption process creates free carriers in the III-V active layer, which reduce the refractive index of the III-V active layer material. The reduction of the guided mode effective index results in a blue shift of the resonance spectrum and hence results in a change in transmission as a function of the density of the free carriers. This effect can be exploited to create an all-optically controlled modulator, as shown in figure 4. By injecting a pump signal at a resonance wavelength of the III-V/SOI cavity, the free carrier generation blue shifts all the resonances, thereby changing the transmission properties of the III-V/SOI racetrack resonator. This allows modulating a probe beam located at another resonance of the III-V/SOI. As this blue shift is due to carrier generation, the speed of this modulation is determined by the free carrier life time, which is about 500ps. Higher operation speed can be obtained by applying a lateral electric field to sweep the carriers out of the active region, thereby reducing the effective carrier lifetime.

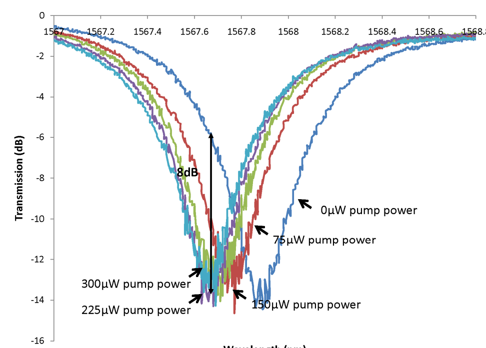

Figure 4 : Static measurement results on the wavelength conversion in a hybrid III-V/SOI microcavity

7. References

[1] G. Roelkens et al: "*Adhesive bonding of inP/InGaAsP dies to processed SOI wafers using DVS-BCB*", Journ. Electrochem. Soc., 153, G1015 (2006).

[2] J. Van Campenhout et al.: *"Electrically pumped InP-based microdisk lasers integrated with a nanophotonic SOI waveguide circuit* ", Opt. Expr. 15, p. 6744 (2007).

[3] H. Park et al.: "*A hybrid AlGaInAs-silicon evanescent preamplifier and photodetector* ", Opt. Expr. 15, 13539 (2007).