III-V/silicon photonic integrated circuits for FTTH and on-chip optical interconnects

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Abstract—**In this paper we review our work in the field of heterogeneous III-V semiconductor/silicon photonic integrated circuits for application in Fiber-to-the-Home optical access networks and chip-scale optical interconnects. Several optical and opto-electronic components realized on this platform are described. The fabrication of the silicon waveguide structures is done in a CMOS pilot line on 200mm wafers.**

Silicon photonics, heterogeneous integration, FTTH, optical interconnect

I. INTRODUCTION

Photonic integrated circuits allow implementing multiple optical functions on a single substrate, thereby reducing the cost and size of photonic systems. These features have attracted a lot of attention in the last decades to realize photonic integrated circuits for telecommunication applications. In recent years, silicon photonics, or more generally CMOS photonics, has generated a lot of interest to realize these photonic integrated circuits in. It has evolved from a niche research field to one of the most prominent technologies for integrated photonics [1]. This is because silicon photonics allows realizing high index contrast waveguide structures and electro-optic components using standard CMOS technology. The high index contrast waveguide structures lead to a dramatic size reduction (and hence cost reduction) of photonic components, while one can leverage the strongly developed CMOS fabrication technology for the industry-scale and nanometer precision realization of these components. Moreover, the material platform itself provides the possibility to densely integrate CMOS electronics with the photonic integrated circuit. A whole myriad of integrated optical components has been demonstrated so far, ranging from low-loss waveguides over resonator structures to more complex wavelength-selective optical devices such as arrayed waveguide gratings and planar concave gratings [2]. The waveguides consist of a 220nm thick and approximately 500nm wide silicon strip lying on top of a 2µm thick SiO_2 cladding layer, which separates the waveguide from the silicon substrate, as shown in figure 1. Typical losses of these silicon-on-insulator (SOI) waveguides are in the range of 2-3dB/cm, allowing for high performance optical circuits. The high omni-directional refractive index contrast in these waveguide structures allows one to tightly confine the optical mode in the silicon waveguide core. This implies that the waveguide pitch can be made very small with negligible cross-talk between the waveguides (on the order of 1µm) and that light can be routed through very sharp bends (on the order of 1µm) with negligible loss. This paves the way to very large scale integration of optical functions on a silicon chip. Besides passive optical components also active electro-optic components were realized on this waveguide platform [3] and the direct integration with CMOS is pursued.

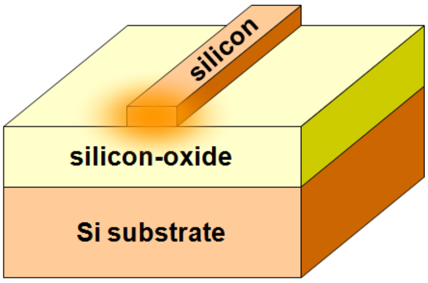


Figure 1: Silicon-on-insulator waveguide structure

While silicon photonics allows realizing compact photonic integrated circuits in the near-infrared, it lacks the possibility to realize efficient, current injection based, light emitters and amplifiers, due to the indirect band gap of silicon. In the scientific community there is a consensus that the way to tackle this problem on the short term is to integrate III-V semiconductor layer stacks on the silicon-based waveguide platform. This heterogeneous integration can be realized using semiconductor wafer bonding technology. The Photonics Research Group has played a pioneering role in this research field, by realizing several III-V semiconductor opto-electronic components heterogeneously integrated on and coupled to the silicon waveguide circuit [4]. Various technologies are available today to realize this heterogeneous integration, including molecular wafer bonding and adhesive wafer

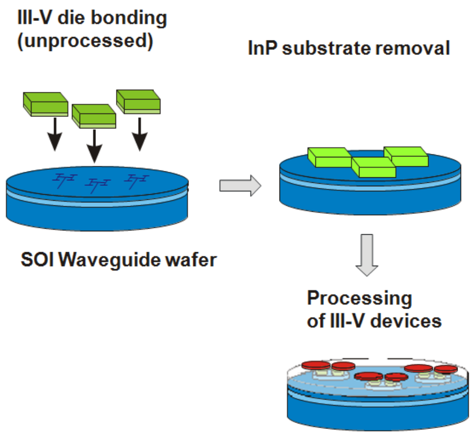


Figure 2: Heterogeneous integration of III-V semiconductor opto-electronic components on top of silicon waveguide circuits

bonding. The Photonics Research Group has focused so far on the use of adhesive bonding using a DVS-BCB polymer bonding agent. The processing sequence is outlined in figure 2. After finishing the fabrication of the passive silicon waveguide circuits on 200mm SOI wafers, III-V dies are bonded, epitaxial layers down, onto the silicon waveguide circuit. These III-V InP/InGaAsP dies do not contain any device features yet, making the positioning of the dies a tolerant and fast process. After curing of the polymer bonding agent, the InP substrate is removed such that the epitaxial layers remain attached to the silicon waveguide circuit. After this layer transfer, the epitaxial layer stack can be processed, lithographically aligned to the underlying silicon features. This allows for the dense integration of active opto-electronic components on a silicon platform, paving the way to the realization of complex active/passive photonic integrated circuits. Several device examples will be discussed in subsequent sections.

One important issue with silicon photonics, especially in the context of telecommunication, is the interfacing of the photonic integrated circuit with the outside world, i.e. an optical fiber. Given the huge difference in waveguide dimensions between the core of a single mode optical fiber (~100μm^2) and the core of a silicon waveguide (~0.1μm^2), efficient coupling between both waveguide structures is far from trivial. Moreover, for many applications this coupling needs to be polarization independent. The large waveguide birefringence due to the high refractive index contrast makes polarization handling on a silicon photonic chip also far from trivial. In order to tackle this problem, diffractive grating coupler structures are used to interface with a standard single mode fiber [5]. These high index contrast gratings are defined in the silicon waveguide layer and allow to efficiently diffract the light out of the waveguide plane to an optical fiber, as shown in figure 3a. In this way, very high fiber coupling efficiency was experimentally obtained (-1.6dB coupling efficiency with a 1dB-bandwidth of 40nm) for one-dimensional grating structures [6]. One-dimensional grating structures still behave very polarization dependent however. In order to tackle the polarization dependence problem, two-dimensional grating structures can be used as shown in figure 3b. These two-dimensional grating structures couple both orthogonal polarizations in the optical fiber to two orthogonal optical waveguides on the chip (with identical polarization of the optical mode in both silicon waveguides). In this way, the two-dimensional grating coupler can directly be used in a polarization diversity scheme that allows for polarization independent operation of a silicon waveguide circuit. This way, we demonstrated 0.15dB of residual polarization dependent loss in a high index contrast waveguide structure [6].

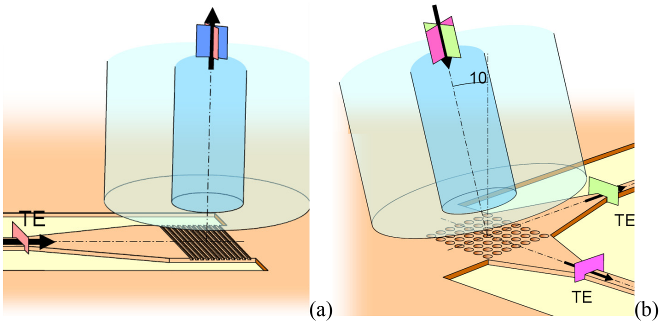
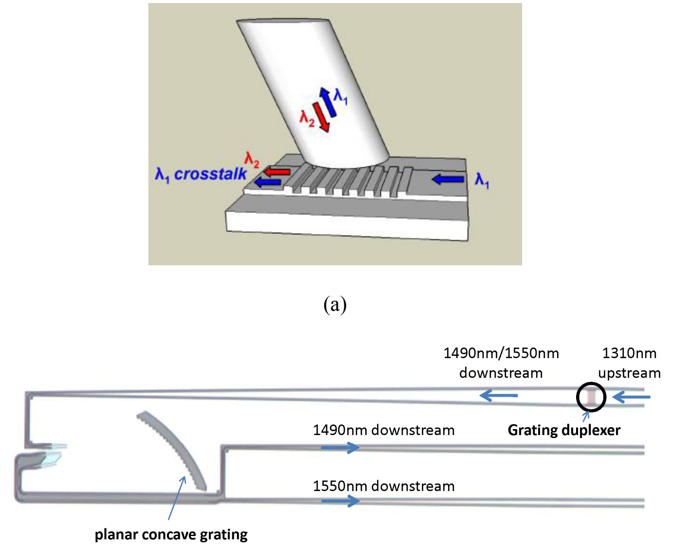


Figure 3: Interfacing a single mode optical fiber to a silicon-on-insulator waveguide circuit using diffraction gratings: one-dimensional grating structures (a) and two-dimensional grating structures (b)

Given these developments in the field of heterogeneous integration and fiber-to-chip coupling, silicon photonic integrated circuits are emerging as a promising platform to implement telecommunication-related optical functions on. Therefore, in the remainder of the paper we will focus on the realization of photonic integrated circuits for Fiber-to-the-Home access networks and for chip-scale optical interconnects.

II. III-V/SOI PHOTONIC IC'S FOR FTTH

Point-to-point Fiber-to-the-Home optical access networks require large volume and low-cost optical transceivers, both at the subscriber and the central office side. From the perspective of the transceiver at the subscriber side, 1310nm is the upstream channel and 1490nm and 1550nm are the downstream channels for data and CATV. The passive optical part of a fiber-to-the-home transceiver has to couple and demultiplex these three communication channels. The grating couplers that were described in the previous section are designed to interface a photonic integrated circuit in a single wavelength band (i.e. the C-band). In order to achieve an interface for the 1300nm wavelength band, the grating design can be modified by using a second entrance waveguide to the grating coupler structure, schematically outlined in figure 4a. Proper design of the grating allows coupling the 1300nm wavelength band and the 1550nm wavelength band to and from the silicon chip, while at the same time providing a spatial splitting of the two wavelength bands. The operation of this wavelength duplexer was experimentally assessed using the device shown in figure 4b, in which a one-dimensional grating duplexer was connected to a planar concave grating demultiplexer. This grating demultiplexer performs both the (de)multiplexing of the 1490nm and 1550nm wavelength band,



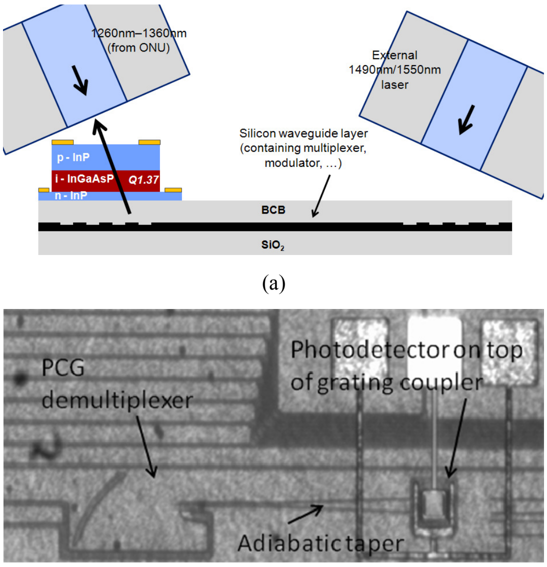
(a)

(b)

Figure 4: Grating duplexer structure to interface a silicon photonic integrated circuit with two wavelength bands (a) and a microscope image of a realized photonic integrated circuit combining a grating duplexer and a planar concave grating for wavelength demultiplexing (b)

while at the same time it also filters out 1300nm-band cross-talk which is transmitted through the grating duplexer [7]. While this device structure only works for a single polarization, a polarization diversity scheme based on a polarization diversity grating duplexer can also be designed.

At the central office side, the 1300nm wavelength band is received while 1490nm/1550nm band signals are transmitted to the subscriber. An elegant way to implement transceivers for the central office side, which directly allows polarization independent operation, is shown in figure 5a. This scheme is based on the integration of a III-V photodetector on top of a silicon grating coupler, in which the photodetector is designed to be transparent for the 1490nm/1550nm wavelength band. By positioning an optical fiber on top of the photodetector/grating stack, the 1300nm signal can directly be detected (0.4A/W responsivity experimentally obtained) with very low polarization dependent loss (<0.5dB over an 80nm wavelength range), while the cross-talk of the 1490nm/1550nm wavelength band is below -30dB. A microscope image of a realized photonic integrated circuit is shown in figure 5b, showing the photodetector integrated on top of the silicon transceiver, implementing the 1490nm/1550nm multiplexing [8].



(a)

(b)

Figure 5: Integration of a III-V photodetector that detects the 1300nm wavelength band signals and is transparent for the 1490nm/1550nm wavelength band: schematic cross-section (a) and microscope image (b)

III. CHIP-SCALE OPTICAL INTERCONNECTS

Due to the continued down-scaling of the transistor size in electronic integrated circuits, the (long-distance) on-chip electrical interconnects are becoming a bottleneck. One approach to tackle this problem is to use optical interconnects for long distance communication on the chip. The silicon-on-insulator material platform is well suited for this optical interconnect application, due to the fact that its processing is compatible with the fabrication of the electronic integrated circuits. All basic functionalities for optical interconnects can be realized on the silicon platform, except for an electrically pumped light source. In order to realize this on an SOI platform, the heterogeneous integration of III-V semiconductors has been proposed. This III-V layer can however also be used for the active optical functionality such as optical modulators, photodetectors and switches. Thereby the function of the SOI photonic layer is purely that of a passive interconnect layer. The footprint of these active III-V devices should be as small as possible, while their power consumption and operation speed should be compatible with the envisioned application. Therefore we studied III-V microdisk resonators integrated on top of a silicon waveguide circuit as a key component to realize the light emission, modulation and switching functionality. The device layout of the microdisk structure is schematically illustrated in figure 6. The microdisk resonator supports whispering gallery mode resonances which are confined at the circumference of the disk. By placing the top metal contact in the center of the disk and using a lateral contact the metallization can be kept away from the optical mode, thereby realizing high quality factor resonances. When forward biased, the quantum wells in the microdisk structure are pumped to population inversion, thereby creating a microlaser structure which evanescently couples out light to the silicon waveguide circuit. This way, 120µW of CW power (1.58µm wavelength) was coupled to the silicon waveguide circuit, using 3.5mA injection current (device diameter: 7.5µm). Single mode operation with a side mode suppression ratio of more than 35dB was obtained, which is due to the small size of the resonator [9]. When the microdisk structure is not biased, the multi-quantum well region is heavily absorbing, thereby resulting in a resonator with very low Q-factor. When the quantum wells are pumped to transparency, high Q-factor resonances can be obtained.

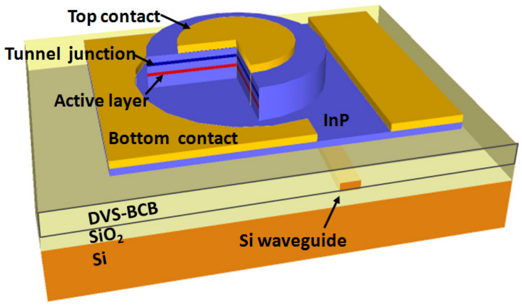
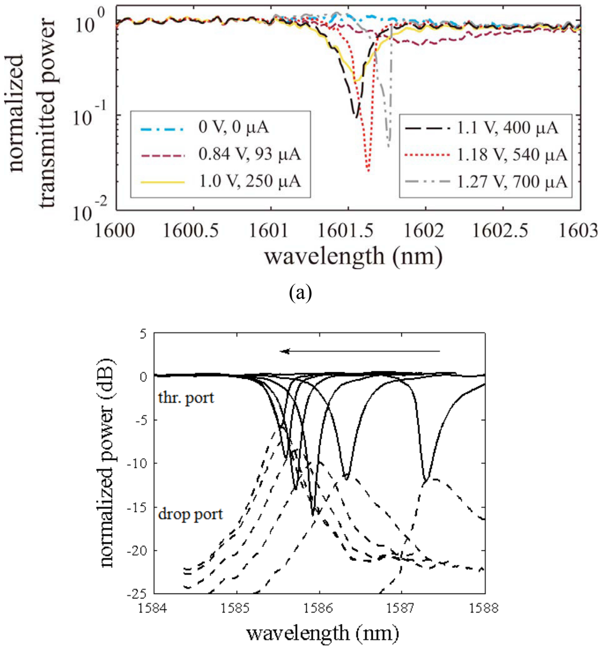


Figure 6: Schematic illustration of the microdisk resonator structure integrated on a silicon waveguide circuit.

This gives us a mechanism to modulate a light beam that is traveling through the silicon waveguide circuit. The change of the microdisk transmission as a function of injected current is shown in figure 7a, clearly showing the occurrence of a resonance dip when the microdisk is pumped to transparency. This way, optical modulation with 6dB extinction ratio at 2.75Gbps was obtained, without the use of special pre-emphasis techniques [10]. Besides its use a modulator, this type of device can also be used as a space switch, by integrating an additional silicon bus waveguide underneath the microdisk resonator. In this case the operation principle is based on the resonance blue-shift when injecting more current into the III-V microdisk, as shown in figure 7b.



(a)

(b)

Figure 7: Schematic illustration of the microdisk resonator structure integrated on a silicon waveguide circuit.

Selecting the current determines whether a wavelength is sent to the through port of the device or whether it is dropped in the second silicon bus waveguide, thereby realizing a wavelength selective space switch. A switching speed of 1.2ns was obtained in this way with a 15dB extinction ratio [11].

IV. CONCLUSIONS

In this paper we outlined a set of III-V/silicon photonic components that can be used for communication applications. We also assessed the important issue of high efficiency and polarization independent optical coupling to a photonic integrated circuit. Other devices such as waveguide integrated photodetectors were also realized, both for the near-infrared wavelength range [12] and the short wave infrared [13], which will find applications in the field of spectroscopic sensing. This shows that the developed III-V/SOI platform can be used in a broader set of applications than telecom, including biomedical, life sciences and environment.

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