Demonstration of a novel III-V-on-Si distributed feedback laser

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Abstract: We present the first experimental demonstration of a novel III-V-on-silicon distributed feedback laser type. All structures defining the laser cavity are defined in the silicon. Alasing threshold of 50mA and a side mode suppression ratio higher than 40 dB is achieved.

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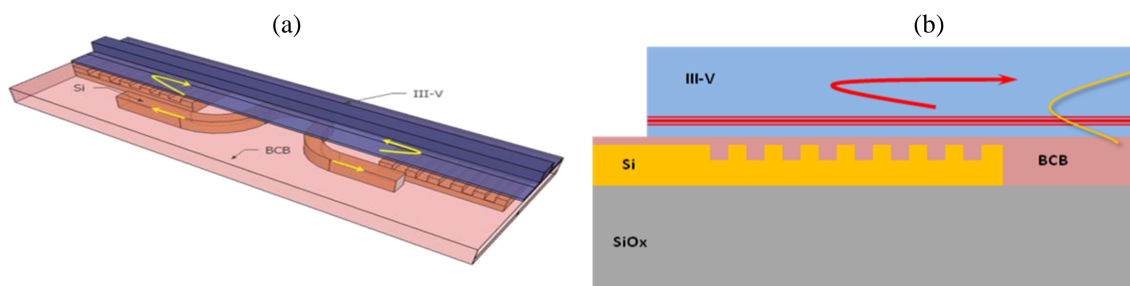
1. Introduction

Silicon-On-Insulator (SOI) is gaining interest as a novel platform for integrated optical circuits. Its large refractive index contrast allows for ultra-compact devices but the interest in this technology stems mostly from the expectation that the maturity and low cost of CMOS-technology can be applied for advanced photonics products. However, the integration of a laser on this platform is hampered by silicon's indirect bandgap. Building light sources, and in particular laser sources, on integrated silicon circuits is a big challenge. In that sense the heterogeneous integration of III-V/silicon lasers combines the best of two worlds. In spite of the rapid progress in this technology since about 2006, the design and fabrication of hybrid silicon lasers present specific challenges and trade-offs. There are many choices to be made, both in terms of the cavity structure, the optical coupling between the silicon waveguide and the III-V waveguide and the technological approach. A relatively large variety of device approaches have been reported in the past years [1]. Two main technologies are used to heterogeneously integrate III-V epitaxial layer stacks on a silicon waveguide circuit: molecular bonding and adhesive bonding. We focus on an adhesive die-to-wafer and wafer-to-wafer bonding process, based on DVS-BCB as a bonding agent, given more relaxed requirements on the III-V wafer surface quality (contamination, particles, roughness). This principle has proven to work in several different configurations [1][2]. A promising method to achieve a high performance laser cavity is to use an intra-cavity double taper structure, using taper-based mode transformers in both the III-V and silicon waveguides [2]. However, the fabrication of taper-based mode converters is not straightforward because of the narrow tips required and the strong dependence of the performance on alignment accuracy. In this paper we propose a new approach to obtain a compact, efficient and single mode hybrid silicon laser, based on an active DBR grating which requires no complex coupling structures such as narrow-tip tapers in the III-V process.



ig. 1. (a) Schematic of the active DBR with the evanescent coupling waveguide in the center of the laser cavity (b) schematic view of a hybrid DBR reflector in the hybrid silicon laser.

2. Laser cavity design

The hybrid platform consists of an SOI substrate with a slab of III-V material bonded on top and a thin bonding layer (DVS-BCB) in between. An optimal laser cavity design should consist of a section where the optical mode is

completely confined to the III-V waveguide layer, while the wavelength selective feedback is provided by structures defined in the silicon, thereby taking advantage of the resolution and accuracy of lithography tools in CMOS fabs. Of course, the laser emission should also be coupled efficiently into the silicon waveguide layer. It would thus be beneficial to think of cavities that do not use an adiabatic taper to couple light between the III-V layer and the silicon waveguides. Besides using resonant cavities in the silicon [3], this can be realized in a DBR-based cavity by using two active DBR gratings with nearly 100% reflection to define the laser cavity and where an evanescent coupling interface is positioned within the laser cavity as the laser output as shown in figure 1. This hybrid laser design offers much simpler device fabrication and helps to reduce the device footprint.

3. Simulation Results

We have simulated the use of DBR reflectors extensively in the context of these hybrid silicon lasers. In a cross-sectional view of the structure, two waveguides can be identified: one in the silicon DBR grating and one in the active layer. In between them there is the bonding layer (DVS-BCB), as shown in Fig 1(b). The III-V region used in the simulation has a multiple quantum well (QW) double heterostructure, which consists of a p-InGaAs contact layer, a p-InP cladding, a quantum well region, and an n-InP bottom cladding layer. The QW region consists of six 8nm thick InGaAsP (1.55um bandgap wavelength) well layers separated by 10nm thick InGaAsP (Eg=1.17um bandgap wavelength) barrier layers. The thickness of both SCH layers is 100nm and the thickness of the n-InP and p-InP layers are 200nm and 1500nm respectively. The silicon rib grating has a height of 400nm, an etch depth of 180nm and a width of 3μm for the DBR parts. Simulations were performed for the cavity reflectors and the coupling section. A 2D simulation based on the open-source eigenmode solver CAMFR [4] to calculate the first-order to first-order mode reflection of the active waveguide is shown in figure 2(a), showing the power reflection as a function of the number of periods and the DVS-BCB thickness, for a grating period of 240nm (for Bragg reflection at 1.55μm), 50% duty cycle and an etch depth of 180nm. The coupling constant κ for two different silicon waveguide heights and two different grating etch depths versus DVS-BCB thickness is plotted in figure 2 (b).

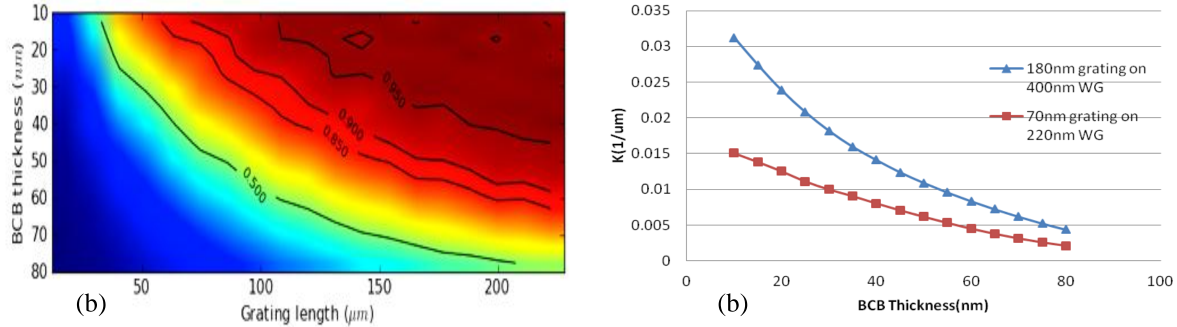


Fig. 2. (a) Grating reflection as a function of the number of grating periods and DVS-BCB thickness (b) Coupling constant κ for a hybrid grating simulated for different grating cross-sections versus DVS-BCB thickness.

3. Fabrication and measurement results

The SOI substrate (200 mm wafer manufactured by SOITEC) is composed of a 400 nm mono-crystalline silicon layer on top of a 2μm thick buried oxide layer on a silicon substrate. The fabrication process begins with the processing of the SOI wafer incorporating a 400 nm thick silicon waveguide layer in a CMOS pilot line. The silicon rib waveguides have a height of 400nm and an etch depth of 180nm. Also the DBR-gratings defining the laser cavity were etched 180nm deep in the 400nm thick silicon layer and had a period of 240nm. Afterwards, a SiO_2 cladding layer was deposited and the wafer was planarized using chemical mechanical polishing (CMP) and an extra wet etching step to reach the silicon waveguide level before bonding. The III-V membrane layer is bonded onto the silicon waveguide circuit using an adhesive BCB die-to-wafer bonding approach [2]. The III–V region consists of the layers as described in the simulation section. After bonding and InP substrate removal, a SiNx hard mask was defined using 320 nm UV contact lithography. ICP etching was used to etch through the InGaAs layer, the InP p-doped layer and the MQW layer using CH4:H2. Figure 3 shows a microscope image of the fabricated device and a scanning electron microscope (SEM) picture of the coupling section in the silicon layer. The active waveguide is encapsulated with DVS-BCB. GeAu/Ni and Ti/Pt/Au contacts were used for the n and p-sides respectively. In this first electrically pumped prototype, the silicon DBR-mirrors were 2 μm wide, had a period of 240nm and were etched 180nm deep in a 400nm high rib waveguide. Each mirror was 350 μm long and both mirrors were separated from each other by 120μm. In the middle between both mirrors we inserted a compact wedge type outcoupling

section in the silicon layer. The light from the laser cavity is coupled out through evanescent coupling and by choosing the coupling length the output power can be engineered. The III-V waveguide above is 2.5 µm wide and depending on the bonding thickness and design can be from 400µm to 800 µm long. This gives enough design flexibility for optimizing the laser for the best power efficiency.

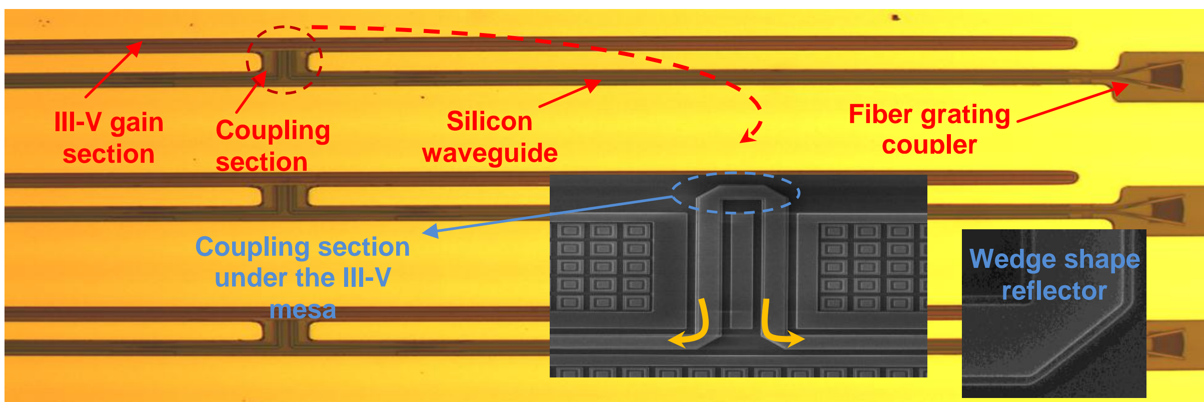


Fig. 3. Microscope picture of the fabricated lasers, showing the coupling section, the III-V integration on silicon (after n-type metallization) and the passive silicon output grating couplers.

In this paper we are presenting the results for a III-V laser of 700 µm length. Single wavelength operation is observed with side mode suppression ratio consistently around 40 dB. The device has a lasing threshold of 50mA and a maximum fiber coupled power of -25dBm at both sides in continuous wave (figure 4). Huge losses due to an error in the fabrication of the wedge corner (almost 6dB loss per 45 degree facet) and 10 dB loss due to the chip to fiber grating coupler and a larger than expected bonding layer thickness (in this demonstration 120nm) reduce the coupling efficiency substantially. Outcoupling will be significantly improved by reducing the bonding layer and replace the wedge corner by a bend coupling section, which will result in mW-level output power [6].

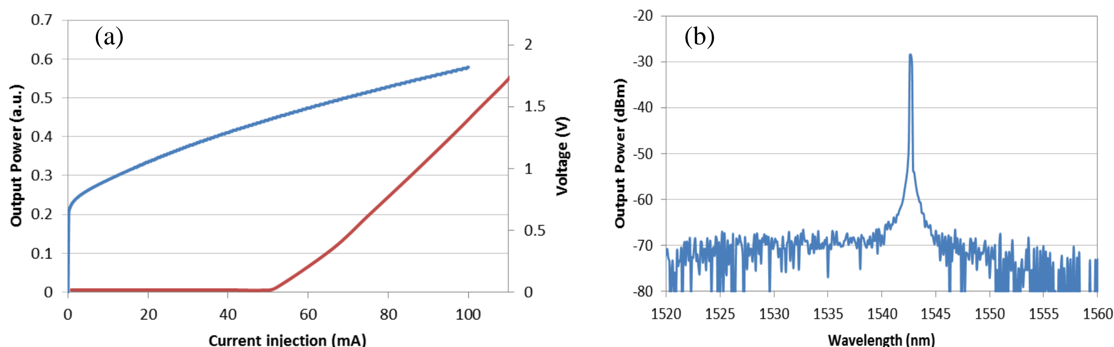


Fig. 4. (a) The L-I-V curve for a single mode laser ;(b) Lasing spectrum of the hybrid single mode laser for 80mA current injection at 20°C

4. Conclusion

We present the first experimental demonstration of a new concept for the realization of III-V-on-silicon hybrid lasers, providing high optical confinement in the III-V waveguide layer, while the wavelength selective feedback elements are implemented in the silicon. This opens up a route towards the large volume realization of single mode lasers with precisely defined emission wavelength on a silicon waveguide platform.

5. References

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