Heterogeneously integrated III-V/silicon distributed feedback lasers

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Heterogeneously integrated III-V-on-silicon second order distributed feedback lasers utilizing an ultra-thin DVS-BCB die-to-wafer bonding process are reported. A novel design exploiting high confinement in the active waveguide is demonstrated. 14mW output power coupled to a silicon waveguide, 50dB side mode suppression ratio and continuous wave operation up to 60°C is obtained.

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Silicon photonics is emerging as an important platform for the realization of high-speed optical transceivers. This is related to the fact that the silicon waveguide circuits, comprising ultra-compact passive waveguide circuitry, high-speed optical modulators and germanium photodetectors, can be fabricated using complementary metal-oxide-semiconductor (CMOS) fabrication technology in large volumes and at low cost [1]. However, the integration of a coherent light source on the silicon platform remains an issue. While electrically driven germanium laser sources have been demonstrated [2], the performance of these devices is still far inferior to what can be achieved using InP-based III-V semiconductors. III-V semiconductor layer stacks can be heterogeneously integrated onto the silicon waveguide circuit using a wafer bonding technique followed by InP substrate removal, which provides a route towards wafer-scale processing of these III-V epitaxial layers, lithographically aligned to the underlying waveguide circuit. In recent years, several device demonstrations were made on this III-V/silicon platform [3], both using a molecular [4] and adhesive bonding approach [5]. In this paper we describe the realization of single wavelength 1550nm distributed feedback (DFB) lasers coupled to a 220nm thick silicon waveguide layer, with waveguide coupled output powers of 14mW, a side-mode-suppression ratio better than 50 dB and a laser linewidth of 1MHz. The coupling to a 220nm silicon waveguide circuit will allow in a later stage to co-integrate high speed devices such as modulators and photodetectors with the single wavelength lasers using the available silicon photonics platform technology as offered by several multi-project wafer run services worldwide.

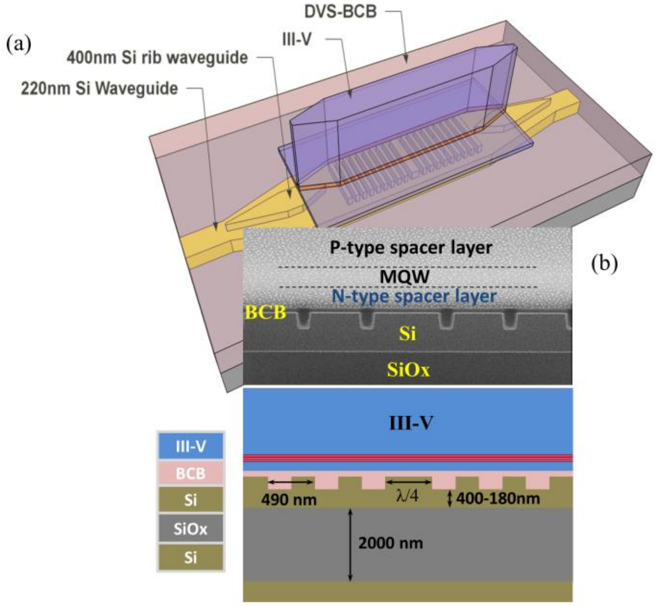

Fig.1. III-V/Si distributed feedback laser design: (a) three-dimensional view on the III-V-on-silicon DFB laser; (b) schematic longitudinal cross-section of the laser structure and SEM picture of the actual device.

The distributed feedback laser structures reported in this paper are based on quarter-wave shifted second order gratings with a Bragg wavelength around 1550nm. The three dimensional layout of the laser cavity is depicted in Figure 1(a), while a longitudinal cross-section of the laser geometry is shown in Figure 1(b). The gratings are defined in a 400nm thick silicon waveguide layer, by a 180nm deep dry etch. The III-V epitaxial layer stack that is used consists of an 200nm thick n-InP contact layer, two 100nm thick InGaAsP separate confinement heterostructure layers (bandgap wavelength 1.17µm), 6 InGaAsP quantum wells (6nm thick, emission wavelength 1.55µm) surrounded by InGaAsP barriers, a 1.5µm thick p-InP top cladding and a 100nm p++ InGaAs contact layer. The confinement factor of the optical mode in the 6 quantum wells is 9.3 %. The use of a 400nm thick silicon waveguide layer in the laser section simplifies the optical coupling between the III-V laser mode, which is completely confined in the III-V mesa and which evanescently feels the silicon grating, and the silicon waveguide layer, compared to the case of direct coupling to a 220nm thick device layer. This optical coupling is realized using a III-V/silicon spotsize converter structure defined by tapering both the III-V and silicon waveguide as shown in Figure 2(a), similar to the structure used in [6]. The III-V taper is a piecewise linear taper that quickly tapers (L= 35µm) from a 3 µm mesa width to an 0.9µm wide waveguide width after which a slower adiabatic taper (L= 150µm) is implemented by tapering both the III-V and silicon waveguide structure. Using a 400nm thick silicon waveguide relaxes the requirements on the required III-V taper tip width: a width of 500nm is sufficient to achieve a high efficiency, low reflection power transfer from the III-V laser mesa to the silicon waveguide as illustrated by the simulation results in Figure 2(b). Since the III-V spotsize converter consists of the same active region as the laser, also this spot-size converter is electrically pumped. After the laser emission is coupled to the 400nm thick silicon waveguide layer, a second spot-size converter (L=30µm) is used to couple to a 220nm strip waveguide. Quarter-wave shifted second order DFB gratings with a period of 480nm and 490nm and a duty cycle of 25% were studied. Since the evanescent tail of the laser mode is interacting with the silicon grating, the actual grating coupling strength depends on the DVS-BCB low index (n=1.54) bonding layer thickness in between the III-V mesa and the silicon waveguide layer. This coupling strength is illustrated in Figure 2(c). Given the good uniformity and reproducibility of the adhesive bonding process [7], good control of the grating coupling strength can be obtained.

The silicon device wafer fabrication is carried out in a CMOS pilot line on 8inch SOI wafers. The process starts with the etching of a 400nm silicon device layer on a 2µm SiO_2 buried oxide layer. In a first etch step 180nm deep gratings are etched together with the silicon rib waveguides used in the spotsize converter structure. In a second etch step, 50nm deep structures are etched in the exposed 220nm thick silicon device layer in order to realize fiber-to chip grating couplers.

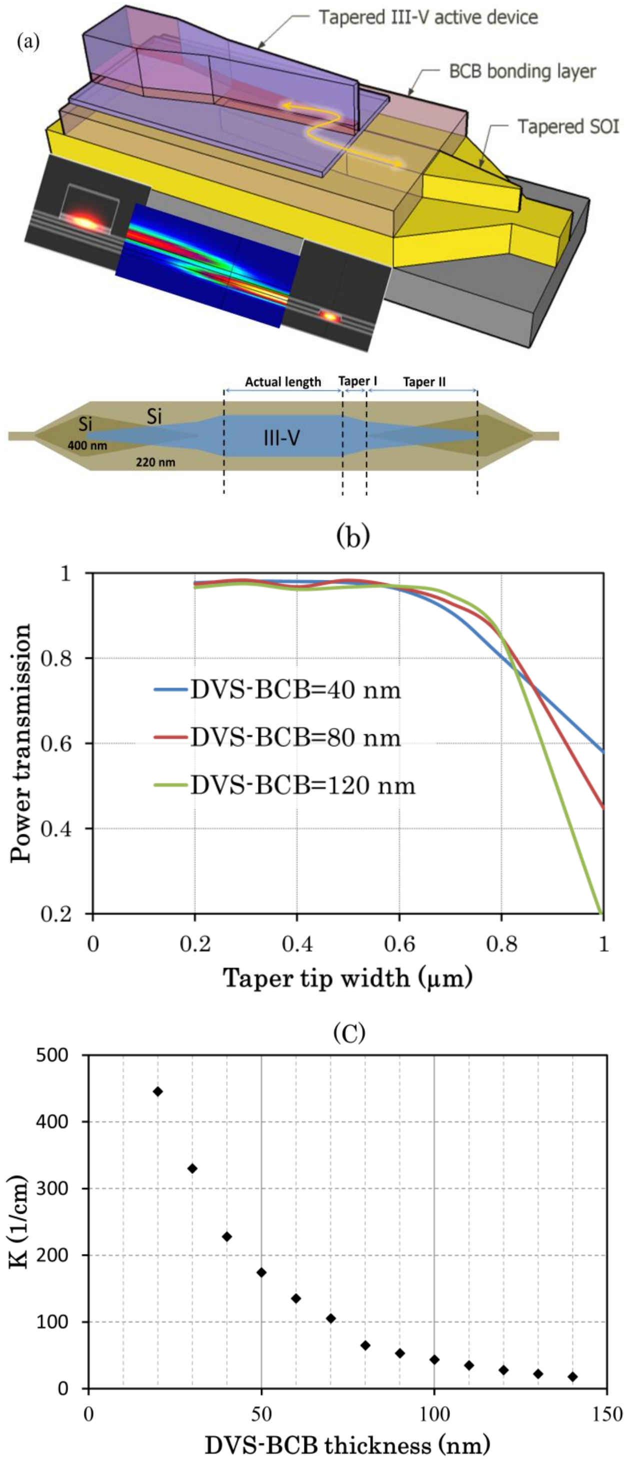

Fig. 2. (a) spotsize converter structure used in this work; (b) simulated power transmission and reflection at the spotsize converter taper tip as a function of taper tip width; (c) grating coupling strength as a function of DVS-BCB thickness for the second order grating structure (490nm period, 25% duty cycle) used in this work.

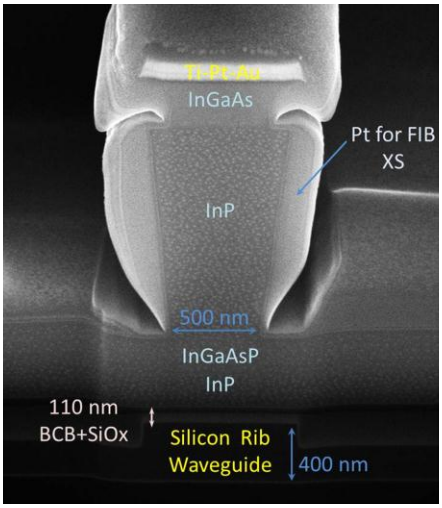

Fig. 3. . Scanning electron microscope images of the III-V spot-size converter taper tip illustrating the 500nm taper tip width close to the active core of the III-V waveguide.

In a final step a 220nm deep etch is used to define the silicon strip waveguides and the transition to the 400nm device layer. After device etching, the wafer is covered with thick SiO$_2$ after which chemical mechanical polishing is used to planarize the wafer in combination with wet chemical etching in buffered HF to expose the top of the 400nm thick silicon waveguides. This way, a quasi-planar wafer surface is obtained, which allows the subsequent heterogeneous integration of the III-V epitaxial layer stack. For the transfer of the laser epitaxy, an adhesive die-to-wafer bonding process with a DVS-BCB adhesive bonding layer is used. This bonding process is described in detail in [7]. The 110nm bonding layer thickness results in a theoretical grating coupling strength of 35 cm^{-1}. After bonding, the InP growth substrate is removed and the III-V laser mesa is defined. In this device demonstration the III-V mesa and spotsize converter are defined through wet etching, using HCl and H$_2$O:H$_2$SO$_4$:H$_2$O$_2$ for the InP and InGaAs/InGaAsP layers respectively. This wet etching technique allowed creating undercut structures in the spot-size converter, which again relaxed the lithography requirements in the definition of the III-V spotsize converter, which was realized using 300nm UV contact lithography. A scanning electron microscope picture of the V-shaped III-V spotsize converter taper tip is shown in Figure 3.

Laser characterization was carried out by collecting the laser emission in a standard single mode fiber using integrated silicon fiber-to-chip grating coupler structures. The coupling efficiency of these grating couplers was characterized on separate structures and used to determine the optical power coupled to the 220nm silicon strip waveguides. The L-I-V curves of the fabricated laser structures were measured both at room temperature and at elevated temperature. The results for a second order grating DFB laser (with a period of 490nm and a device length - not including the spotsize converter - of 680 µm) are shown in Figure 4. At 20°C and a 160mW drive current an optical output power of 14 mW coupled into the silicon waveguide is obtained, with a threshold current of 35mA. The characteristic temperature T$_0$ of the laser is 80 K. The slope efficiency of the laser is 0.135W/A at 20°C. At 60°C still 4mW optical output power is obtained. The series resistance of the laser was 7.5Ω. Figure 5(a) and 5(b) show the laser spectrum for two second order DFB lasers with a grating period of 480nm and 490nm respectively (both a broad wavelength scan and a narrow wavelength scan, measured with a 15MHz resolution spectrum analyzer), showing clearly single mode operation with a side mode suppression ratio of more than 50dB. Single mode operation was observed over the whole laser drive current range, indicating that no significant spatial hole burning occurs. Finally, the laser linewidth was characterized using a delayed self-heterodyne measurement setup, using 22.5km of optical fiber delay and an 80MHz acousto-optic modulator. These measurements indicate a laser linewidth of 1MHz.

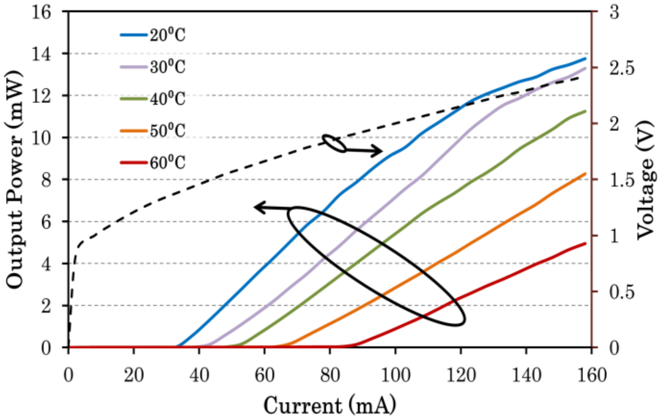

Fig. 4. L-I-V curves at different temperatures for a 490nm period second order DFB laser.

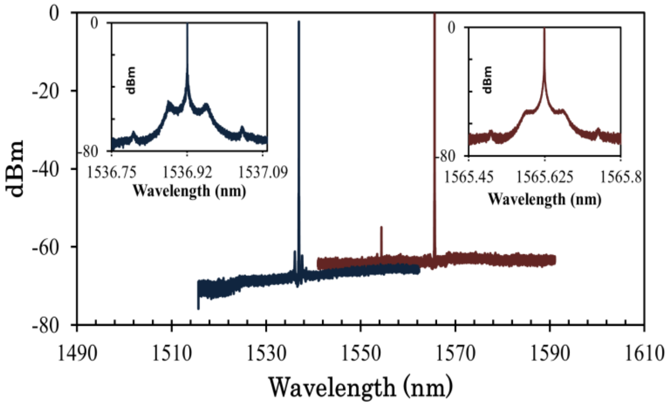

Fig. 5. Spectral characteristics of two second order DFB lasers (480nm period and 490nm period), illustrating single mode emission. The insets show the high-resolution spectra.

In conclusion, heterogeneous III-V/silicon DFB lasers with high optical confinement in the III-V laser mesa coupled to a silicon strip waveguide circuit were realized. The good device performance allows its use both for short-distance and long-distance optical communication. This demonstration paves the way for the realization of advanced III-V/silicon transmitter modules comprising

III-V/silicon DFB lasers, silicon optical modulators and Ge photodetectors.

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