Heterogeneous III-V/silicon photonic integrated circuits

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Abstract: In this paper we review our work in the field of III-V/silicon photonic integrated circuits operating in the communication wavelength window. Heterogeneously integrated lasers on silicon waveguide circuits using adhesive and molecular bonding are described.
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1. Heterogeneous integration

Silicon photonics is becoming an integration platform of large interest for optical datacom and telecom applications. The main driver behind this interest is the fact that compact photonic integrated circuits can be realized using CMOS fabrication tools in large volumes and at low cost. High performance passive waveguide circuits, high speed germanium photodetectors and low power consumption modulators have been demonstrated on this platform. Integrating laser sources and optical amplifiers on these silicon photonic integrated circuits is of paramount importance to provide a route towards scaling up the complexity of these circuits. Many approaches to this problem are currently being considered, including the use of germanium lasers [1], erbium-doped AlOx layers on SiN waveguide circuits [2] or the use of off-chip flip-chip mounted laser sources [3]. While the germanium laser would be the ultimate solution, the performance of these devices is still far inferior to what can be achieved with III-V semiconductors. Erbium-doped devices require an external pump laser and as such complicate the circuit design and do not allow for ultracompact devices that are directly modulated. While external laser sources are currently being used in first commercial products, this approach does not scale well to more complex circuits with large arrays of lasers nor does it allow easy integration of optical amplifiers. In order to exploit the well-developed III-V semiconductor laser technology in the context of silicon photonics, heterogeneous integration – through adhesive or molecular wafer bonding- of III-V semiconductors on silicon waveguide circuits is an appealing approach. In this context we have developed an adhesive die-to-wafer bonding process using DVS-BCB as the adhesive bonding agent [4]. Also III-V on silicon devices based on the molecular bonding technology of CEA-LETI were demonstrated. Both technologies have advantages and disadvantages. While the adhesive bonding process is more forgiving in terms of wafer surface quality compared to molecular bonding, leading to a high yield bonding process, it is not accepted in CMOS front-end processing, thereby restricting the processing of the III-V components to a III-V fab, which is not the case for molecular bonding. In this paper we elaborate on the demonstration of 1550nm and 1300nm heterogeneously integrated lasers based on these technologies.

2. Heterogeneously integrated laser sources

Laser sources are of key importance for silicon photonic integrated circuits. Depending on the application different types of lasers are required, both in terms of wavelength and functionality. Several laser geometries were demonstrated over the past years on the III-V on silicon platform, including single wavelength distributed feedback lasers, tunable lasers, multi-wavelength lasers, micro-disk lasers and micro-lasers based on resonant cavity mirrors.

2.1 Distributed feedback lasers

Distributed feedback (DFB) lasers based on quarter wave shifted first order or second order Bragg gratings are key components for optical interconnect applications. While in a classical III-V semiconductor DFB laser the grating is defined using e-beam lithography in a layer close to the active region, on the III-V on silicon platform one can leverage the state-of-the-art deep UV lithography tools to pattern the gratings in the silicon waveguide layer on a wafer-scale and realize III-V on silicon DFB lasers without requiring regrowth. While the concept of a DFB laser is relatively straight forward, there are several device variations on the III-V on silicon platform. In fact, one can opt for a situation where the optical mode is predominantly confined to the silicon device layer and where the tail of the optical mode overlaps with the quantum well gain region [5], or one could prefer to predominantly confine the optical mode to the III-V gain material while the tail of the mode feels the grating in the silicon waveguide underneath [6]. The second approach has several advantages such as maximum modal gain and less sensitivity to silicon grating etch depth variations. It however requires a spotsize converter structure to couple efficiently to the silicon device layer, which is less critical in the silicon-confined geometry. Both laser cavity geometries were evaluated as shown in Figure 1, where the schematic of a 1300nm silicon-confined laser structure and that of a 1550nm III-V-confined laser structure is shown. The single sided optical output power was 3mW and 5mW respectively, coupled to a silicon waveguide circuit underneath. CW operation up to 60°C was obtained in both cases with more than 40dB side-mode-suppression-ratio (SMSR).

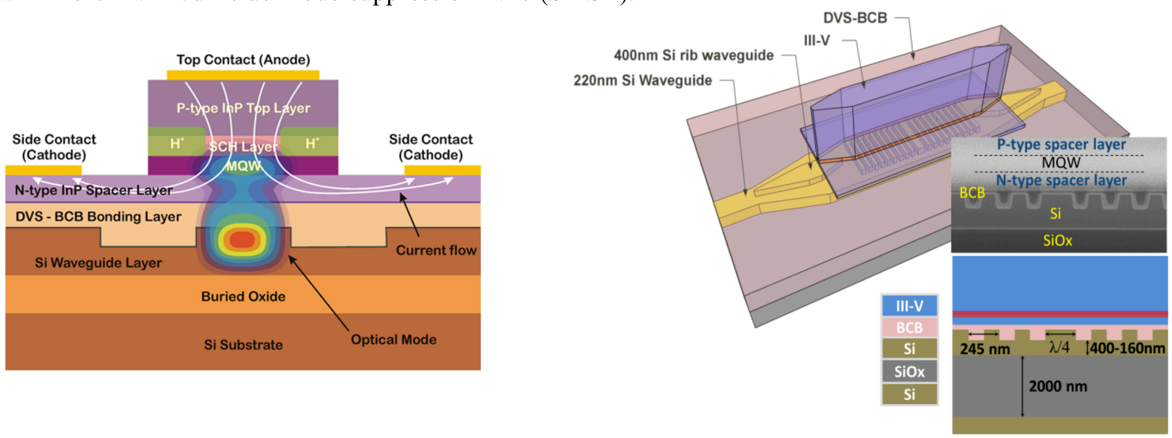


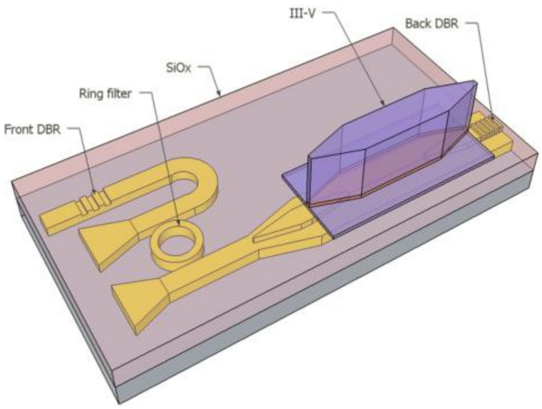
Figure 1:Approaches to a III-V on silicon distributed feedback laser: (a) silicon-confined geometry; (b) III-V-confined geometry

2.2 Tunable lasers

In some applications single wavelength operation combined with several nanometer wavelength tuning range is required. On the III-V on silicon platform this can be realized by combining optically broadband amplification in a III-V on silicon amplifier with a wavelength selective element implemented on the silicon device layer. This wavelength selective element can be a ring resonator structure that is thermally tuned. Since the heating of the ring resonator nearly doesn't affect the gain medium no power penalty occurs. The architecture of this laser geometry is shown in figure 2(a) and provides 10-20nm wavelength tuning [7]. Optical output powers in the range of 10mW are obtained, together with CW operation up to 60°C and more than 45dB SMSR. Recently, even wider wavelength tunability was demonstrated using the Vernier effect in two intra-cavity ring resonators.

2.3 Multi-wavelength lasers

Multi-wavelength lasers (MWL) are attractive devices for use in high-capacity WDM networks or as digitally tunable lasers. They can be realized by integrating a semiconductor amplifier array and a wavelength demultiplexer within a laser cavity. The optical demultiplexer filters the amplified spontaneous emission (ASE) coming from the amplifier and if the gain provided is sufficient to overcome the intra-cavity losses and the mirror losses, the device will start lasing at the wavelengths determined by the demultiplexer. On the III-V on silicon platform the wavelength demultiplexer functionality can be implemented using an arrayed waveguide grating or a ring resonator array filter. In Figure 2(b) the geometry of an AWG-based device is shown. 4-channel devices were experimentally realized with a 250GHz and 200GHz channel spacing for ring-based MWL and AWG-based MWL respectively. Output powers of 5mW and 7mW per channel were obtained, together with CW operation up to 60°C and a SMSR of 45dB [8].



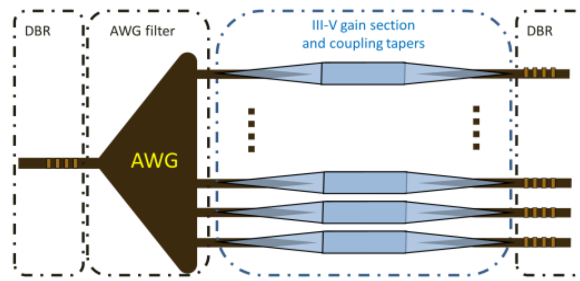
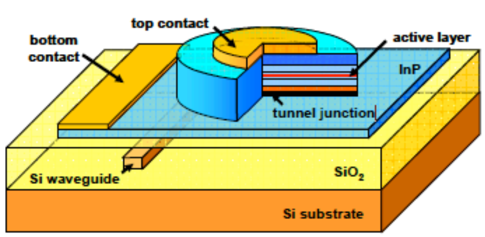


Figure 2: (a) Tunable laser configuration based on a thermally tuned intra-cavity silicon ring-resonator ; (b) multi-wavelength laser based on an intra-cavity silicon arrayed waveguide grating.

2.4 Micro-lasers

While the laser sources discussed above provided mW level optical output power for longer distance optical interconnect applications, other applications such as intra-chip optical interconnects require low-power consumption, small footprint devices. For this type of applications, micro-cavities can be used. The first successful electrically injected micro-laser was a micro-disk laser which supports a whispering gallery mode that evanescently couples to an underlying silicon waveguide circuit [9]. These devices are electrically injected by making use of a central top contact and a side contact, such that the optical mode does not feel the presence of the metallization. In order to further reduce the modal loss in the laser cavity a tunnel junction was used to avoid highly doped and absorbing p-contact layers, as shown in figure 3(a). While this device has a sub-mA threshold current and allows coupling about 100uW of optical power to the silicon waveguide layer, the operation wavelength is determined by the III-V microdisk diameter and is subject to mode hopping when the ambient temperature changes or due to self-heating when the laser drive conditions change. To mitigate these issues with wavelength control a novel type of III-V on silicon microlaser structure is currently being studied based on resonant grating cavity mirrors, as shown in figure 3(b) [10]. In this case the quarter-wave shifted grating structure provides a narrow-band reflection that is completely controlled by the silicon device fabrication. First experimental results using optically pumping of a 50µm long device are promising and an electrically injected version of such a micro-laser is currently being fabricated.



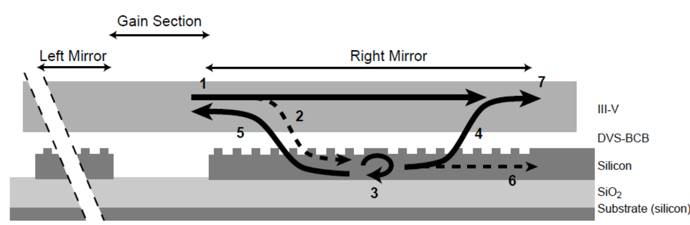


Figure 3: (a) microdisk laser geometry ; (b) resonant cavity grating mirror laser geometry.

4. References

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