InAs/GaAs quantum dot 1.3 μm DFB laser heterogeneously integrated on a silicon waveguide circuit

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ABSTRACT

We demonstrate the first single mode InAs/GaAs quantum dot distributed feedback laser at 1.3 μm wavelength heterogeneously integrated on a Si photonics waveguide circuit. High temperature operation with continuous wave lasing up to 100°C is shown. Threshold current densities as low as 353 A/cm^2 were measured. Single mode lasing around 1320 nm with a side-mode suppression ratio of 40 dB is obtained. These devices are attractive candidates for uncooled wavelength division multiplexing (WDM) transceivers in data centers.

Keywords: Quantum dot lasers, silicon photonics, distributed feedback laser

1 INTRODUCTION

In the present Big Data era, the demand for higher bandwidths is increasing at an unprecedented pace. This trend requires high-performance interconnects that can sustain this high bandwidth without consuming excessive energy. Silicon photonics is emerging as an important platform for the realization of high-speed, power-efficient optical transceivers. However, currently the cost-effective integration of the light source limits silicon-based photonic integrated circuits (PIC) deployment in these fields. On-chip lasers operating at high ambient temperature and with low-loss coupling to the silicon waveguide circuits are essential in order to become a competitive technology for that matter.

Due to the three dimensional confinement of carriers, InAs/GaAs quantum dot (QD) lasers inherently have a more stable performance over the 20°C-100°C temperature range compared to quantum well lasers [1]. Furthermore, they can achieve very low threshold current densities [2] and because of the way QDs are grown they have a wider gain spectrum compared to conventional quantum well lasers making this material system an excellent candidate for creating multi-wavelength transmitters.

The integration of QD lasers on the silicon photonics platform, leveraging the well-developed CMOS fabrication infrastructure and its economy of scale, can provide a distinct cost advantage over other optical technologies. At the same time it allows lower power consumption and enables the scaling of the aggregate bandwidth of transceivers to the Terabit/s range.

There are many possible ways to integrate lasers with silicon optical circuits ranging from hetero-epitaxy of III-V materials [3] to flip-chip bonding [4] and wafer bonding [5]. Many wafer-bonded approaches use a metal layer between the silicon and the GaAs wafers to facilitate bonding [6], which complicates the coupling to an underlying silicon waveguide circuit. Wafer-bonded QD lasers without a metal layer have recently been demonstrated [7]. Since both electrical contacts are now formed on the III-V, low-loss coupling of the laser light to a silicon waveguide is possible. This allows for the integration of heterogeneous III-V-on-Si quantum dot lasers with high-quality Si photonic components.

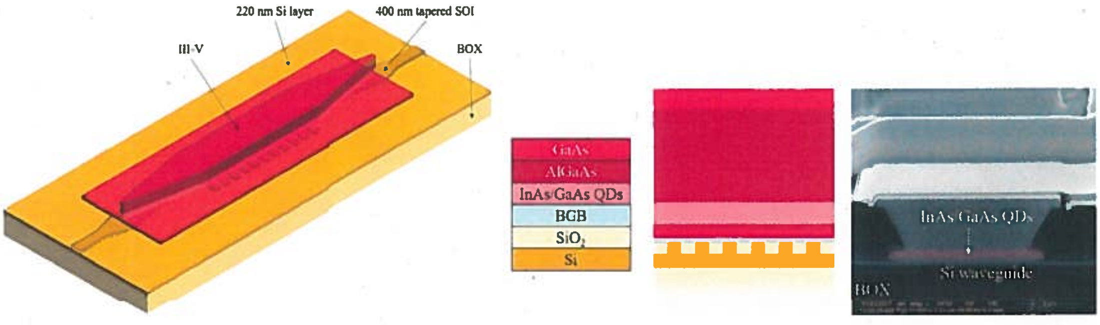
Distributed-feedback (DFB) lasers are crucial devices, providing longitudinal single-mode emission with a narrow line width. They are indispensable for wavelength division multiplexing (WDM) systems. In this paper we demonstrate the first single mode InAs/GaAs quantum dot DFB laser on a silicon substrate with coupling to a silicon waveguide. The DFB laser structure reported in this paper is based on second order gratings defined in the silicon circuit with a Bragg wavelength around 1320 nm.

2 DEVICE DESIGN AND FABRICATION

The device geometry of the DFB laser is shown in Fig. 1(a). The laser cavity consists of a DFB grating defined in the silicon waveguide layer with the III–V gain region bonded on top. The III-V gain section is 1000 μm long (not including the 215 μm-long spotsize converters on each side). Second order DFB gratings were used with a grating period of 400 nm and a duty cycle of 70%, which corresponds with a Bragg wavelength of 1320 nm. The confinement factor of the optical mode in the quantum dot active region is around 8.9 %. A 215 μm-long tapered spotsize converter is used to couple the light from the hybrid gain section into the passive silicon waveguides. The III-V taper is a piecewise linear taper that quickly tapers (L = 35 μm) from a

3.7 μm mesa width to an 1.7 μm wide waveguide width after which a slower adiabatic taper (L = 180 μm) is implemented by tapering both the III-V and silicon waveguide structure.

A cross-sectional diagram of the III-V-on-silicon waveguide structure is depicted in Fig. 1(b). It consists of a planarized SOI wafer containing the silicon waveguides and gratings defined in a 400 nm thick silicon waveguide layer using 193 nm deep UV lithography (180 nm etch depth). The GaAs quantum dot epitaxial layer stack is adhesively bonded to the planarized silicon-on-insulator (SOI) using a 60 nm-thick divinylsiloxane-bisbenzocyclobutene (DVS-BCB) bonding layer. The III-V active region consists of 9 layers of InAs QDs, with a total thickness of 352 nm. The InAs/GaAs QD core region is clad in p-type and n-type $Al_{0.4}Ga_{0.6}As$/GaAs layers, 1.8 μm and 220 nm thick respectively. The epitaxial layer stack was grown by Innolume.



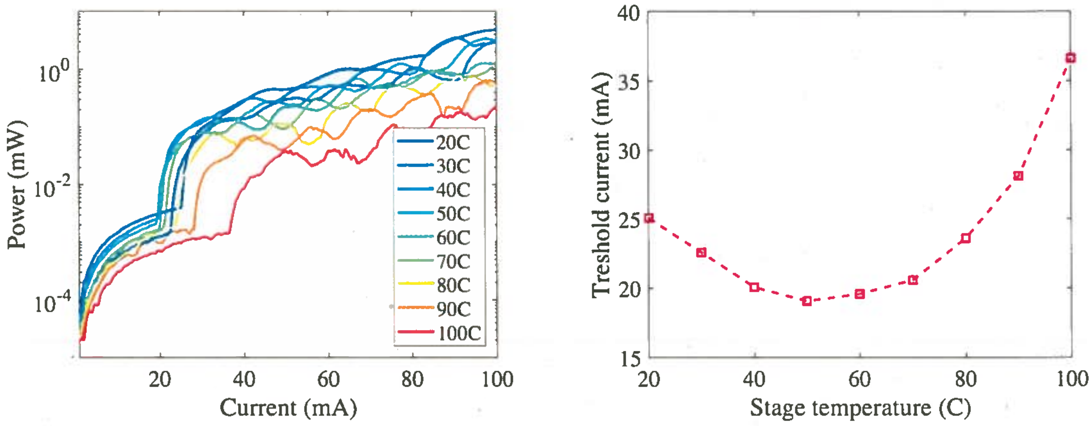
(a) (b) (c)

Figure 1. III-V/Si distributed feedback laser design: (a) 3D view of the III-V-on-silicon DFB laser; (b) schematic cross-section of the laser structure; (c) SEM picture of the actual device.

To fabricate the DFB lasers the III-V mesa and spotsize converter are defined through wet etching, using Citric acid:H_2O_2 and KI:I_2:H_2O for the GaAs/InAs and AlGaAs layers, respectively. This wet etching technique allows creating undercut structures in the spot-size converter, which relaxes the lithography requirements in the definition of the III-V spotsize converter, which was realized using 300 nm UV contact lithography. A scanning electron microscope picture of the reverse trapezoidal III-V mesa is shown in Fig. 1(c).

3 DEVICE CHARACTERIZATION

The laser characterization is carried out by coupling the output of the DFB laser to a standard single mode fiber through a fiber-to-chip grating coupler. The measurements were carried out with the device on a thermo-electric heater set at temperatures ranging from 20°C to 100°C.



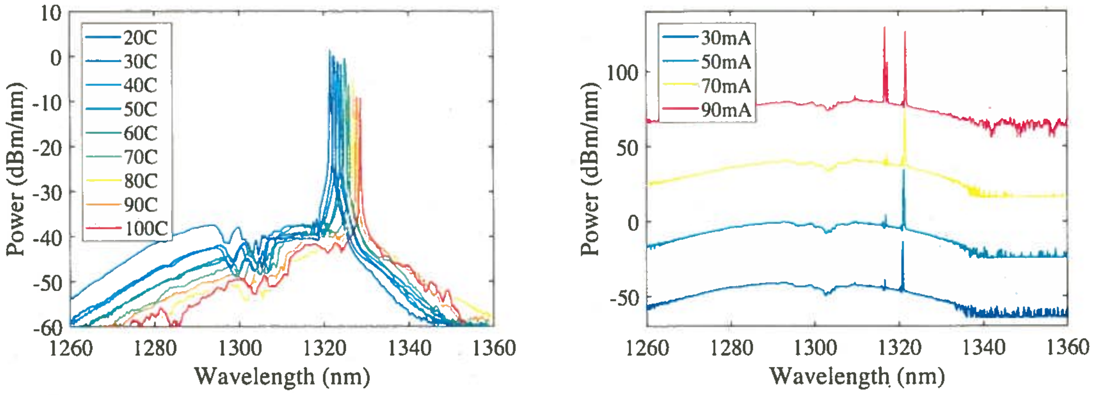
(a) (b)

Figure 2. (a) LI curve as a function of temperature. Power in the waveguide is plotted. (b) Threshold current data as a function of stage temperature.

The continuous wave (CW) light-current (LI) characteristic of the DFB laser is shown in Fig. 2(a), as a function of temperature. Lasing is observed up to 100°C. We measure output powers up to 2.5 mW in the waveguide at room temperature. The ripple observed in the LI characteristics are attributed to parasitic reflections from the grating coupler used for fiber coupling and reflections at the taper tip of the III-V material.

The CW threshold current as a function of stage temperature is shown in Fig. 2(b). The lowest threshold current is 19 mA, reached at 50°C. This corresponds with a threshold current density of 353 A/cm^2. At lower temperatures the threshold current decreases with increasing temperature. This is due to the detuning of the Bragg wavelength and the gain peak: when increasing the temperature, the gain shifts to longer wavelengths and by this matches better with the Bragg wavelength of the grating. At temperatures above 55°C, the threshold current starts increasing with increasing temperature.

The optical spectrum as a function of temperature for a drive current of 50 mA is plotted in Fig. 3(a). Laser emission at 20°C is observed around 1321 nm. With increasing temperature the laser output wavelength shifts to longer wavelengths with a temperature coefficient of 0.1nm/°C. We see single mode operation and a side-mode suppression ratio of 40 dB. Fig. 3(b) shows the optical spectrum as a function of drive current at room temperature. At higher drive currents (e.g. from 90 mA at 20°C) higher order modes appear. This is due to lateral higher order modes that exist in the laser mesa. These modes have a similar optical confinement in the active region and therefore experience a similar level of gain. They have a slightly lower effective index and thus a lower Bragg wavelength than the fundamental mode. At high drive currents these higher order modes start to couple to the fundamental mode in the silicon waveguide due to an imperfect taper in the III-V.



(a)

(b)

Figure 3. (a) Optical spectrum for a drive current of 50 mA as a function of temperature: single mode operation with a SMSR of 40 dB; (b) Optical spectrum for different drive currents at room temperature. The different spectra are shifted 40 dB apart.

4 CONCLUSION

This paper demonstrated the first single mode quantum dot DFB laser on a silicon substrate with efficient coupling of light to a silicon waveguide. We demonstrated high temperature operation with CW lasing up to 100°C. Threshold current densities as low as 353 A/cm^2 were measured. The laser showed single mode behavior with a side-mode suppression ratio of 40 dB. The device performance is currently limited by the suboptimal III-V tapers, resulting in residual reflections, extra losses and the existence of higher order modes. We expect significant improvement with better III-V tapers. These devices are attractive candidates for uncooled WDM systems in data centers.

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