Silicon-Integrated Hybrid-Vertical-Cavity Lasers for Life Science Applications

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The integration of efficient laser sources on silicon would enable fully integrated silicon photonic circuits with a high degree of functionality and performance complexity for many applications1. Different integration concepts have therefore been suggested, where one such technique is the heterogeneous integration of a vertical-cavity laser (VCL), referred to as a hybrid VCL. It is promising as it has potential to offer low drive currents, high modulation bandwidths, and small footprint2-4. In-plane emission with waveguide-coupling can be achieved by an intra-cavity waveguide embossed with a weak diffraction grating, as an example5. Integration of such short-wavelength laser sources on a silicon-nitride (SiN) waveguide platform on silicon may enable fully integrated silicon photonic circuits for applications not only in short-reach optical interconnects but also in life science and bio-photonics. Most biological species and processes are probed in the visible and near-infrared (400-1000 nm wavelengths), and of particular interest is the therapeutic window in the very-near-infrared (750-930 nm wavelengths) where there is minimal photo-damage to cells and negligible water absorption.

As a first step in realizing short-wavelength hybrid VCLs with in-plane emission coupled to a SiN waveguide, we have developed a technique to produce high performance 850-nm hybrid VCLs with out-of-plane emission. It is based on adhesive bonding of epitaxial AlGaAs-material onto a dielectric distributed Bragg reflector (DBR) on silicon6-8. We have fabricated devices with surface emission having sub-mA threshold current, >2 mW output power, and 25 Gbit/s modulation speed8. We have also shown experimentally that the bonding layer thickness can be used to optimize a certain performance parameter at a given temperature or to minimize the variation of performance over temperature8.

Fig.1 Schematic cross-section of our 850-nm hybrid VCLs: surface-emitting design (top), and in-plane emitting design with SiN-waveguide coupling (bottom).

Our top-emitting hybrid VCL design is shown in Fig.1, where the AlGaAs-material consists (from bottom to top) of an n-doped AlGaAs contact/current spreading layer, an active region with five 4-nm-thick InGaAs/AlGaAs quantum wells (QWs), a 30-nm-thick p-doped Al0.3Ga0.7As layer for the formation of an oxide aperture, and a p-doped 23 pair AlGaAs DBR. The dielectric DBR deposited on Silicon is a 20-pair SiO2/Ta2O5 DBR. The bonding layer consists of a thin layer of SiO2 (deposited on the dielectric DBR) and an ultra-thin layer of divinylsiloxane-bis-benzocyclobutene (DVS-BCB). The DVS-BCB layer is used as the adhesive bonding agent6, and its thickness is kept constant while the thickness of the SiO2 layer is used to control the bonding layer thickness. Fig. 2 shows scanning electron microscopy (SEM) images of a device cross-section, and measured steady-state characteristics for a 10 µm oxide aperture device with a ~65 nm-thick bonding layer, resulting in an ~853 nm resonance wavelength at 25°C. The slope efficiency is ~0.55 W/A at 25°C.
To be able to demonstrate in-plane emission with SiN waveguide coupling from our hybrid 850-nm VCLs, our next step is to add a SiN waveguide structure with embossed grating on top of the dielectric DBR, before adhesively bonding the AlGaAs-material (Fig. 1, bottom). So far, based on numerical simulations, we have designed a device that is predicted to yield a slope efficiency of ~0.3 W/A at 25 °C for the light coupled to a single-mode waveguide, while maintaining a sub-mA threshold current for the lasing. The single-mode SiN waveguide core is 300-nm-thick and 500-nm-wide. Since the cavity field is much wider (defined by oxide aperture) than the width of the single-mode waveguide, a tapering of the waveguide width is needed between the grating and the single-mode waveguide. The design work consisted of three parts, where the first part was to investigate (using FIMMWAVE optical mode solver) the required thickness of the top and bottom SiO2 waveguide cladding layers to prevent guided light in the waveguide to leak away into the high index AlGaAs-material or dielectric DBR and Si substrate. The second part was to compute (using Lumerical 2D-FDTD analysis) the fraction of the light incident on the grating and structure below that is coupled into the SiN waveguide. With this information, a final third part (using 1D TMM calculations) was performed to calculate the threshold gain and estimate the slope efficiency. As can be seen in Fig. 3, a slope efficiency >0.3 W/A can be achieved for a threshold gain <1000 cm⁻¹, which is required for sub-mA threshold currents.

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References:
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