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 applications[1]. 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 footprint[2-4]. In-plane emission with waveguide-coupling can be achieved by an intra-cavity waveguide embossed with a weak diffraction grating, as an example[5]. 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 silicon[6-8]. We have fabricated devices with surface emission having sub-mA threshold current, >2 mW output power, and 25 Gbit/s modulation speed[8]. 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 temperature[8].

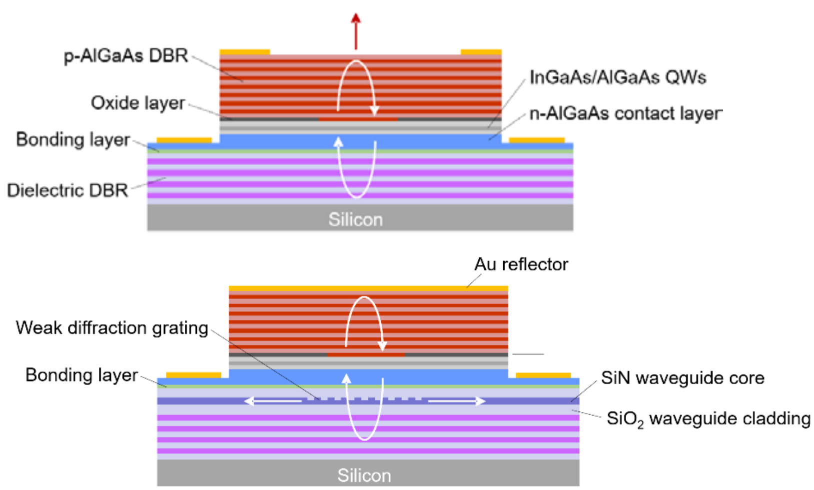

Fig.1 Schematic cross-section of our 850-nm hybrid VCLs: surface-emitting design (top), and in-plane emitting design with SiN-waveguide coupling (bottom).

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 $Al_{0.98}Ga_{0.02}As$ 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 SiO_2/Ta_2O_5 DBR. The bonding layer consists of a thin layer of SiO_2 (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 agent[9], and its thickness is kept constant while the thickness of the SiO_2 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.

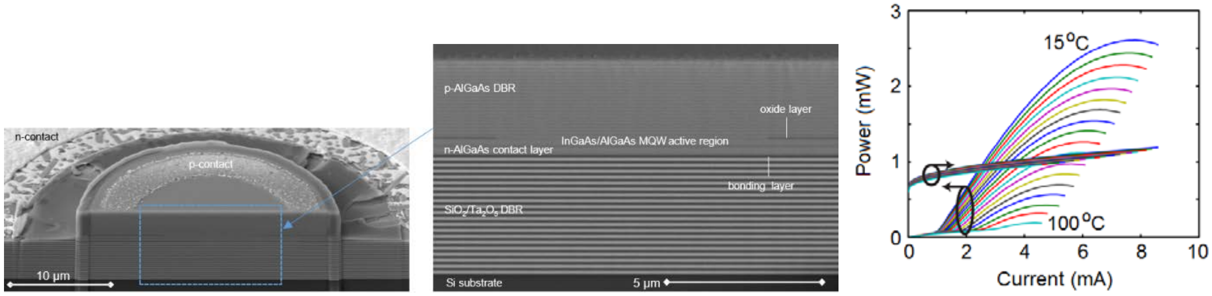

Fig. 2 SEM images of fabricated top-emitting hybrid VCL cross-section after focused ion beam etching (left and middle), and measured steady-state optical output power and voltage drop versus drive current and ambient temperature for a device with a ~65 nm bonding layer thickness and 10 µm oxide aperture (right).

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[10]. 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 SiO_2 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.

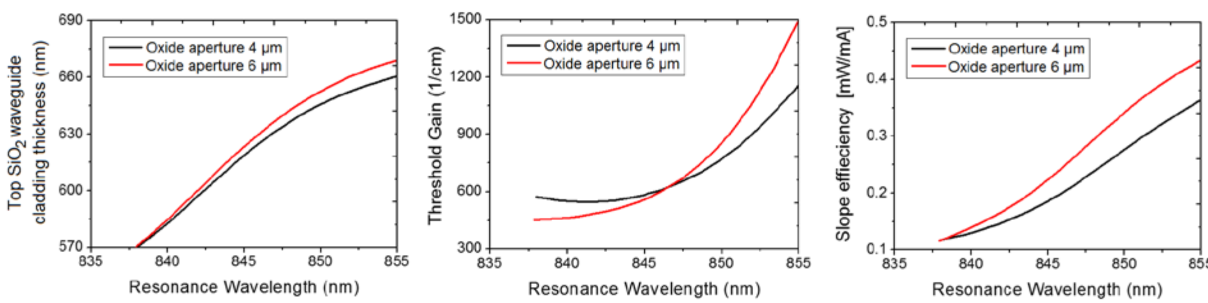

Fig.3 Calculated resonance wavelength, threshold gain, and slope efficiency versus top SiO_2 waveguide cladding thickness for our 850-nm-wavelength hybrid VCL design with in-plane coupling to a single-mode SiN-waveguide. The bottom SiO_2 waveguide cladding thickness is 900 nm, and the grating period, duty cycle, and etch depth are 525 nm, 50%, and 30 nm, respectively.

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