Silicon-integrated short-wavelength VCSELs

Emanuel P. Haglund,[1]* Sulakshna Kumari,[2,3] Erik Haglund,[1] Johan S. Gustavsson,[1] Roel Baets,[2,3] Gunther Roelkens,[2,3] and Anders Larsson[1]

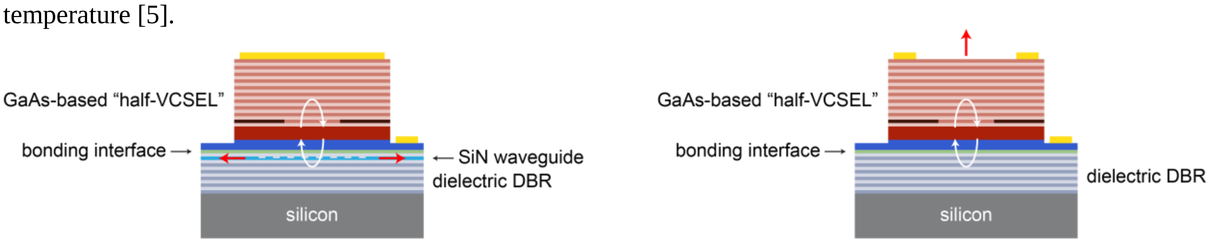
[1]*Photonics Laboratory, Department of Microtechnology and Nanoscience, Chalmers University of Technology, Göteborg, Sweden*
[2]*Photonics Research Group, INTEC Department, Ghent University–IMEC, Belgium*
[3]*Center for Nano-and Biophotonics, Ghent University, Belgium*
**emanuel.haglund@chalmers.se*

Summary: GaAs-based hybrid-cavity VCSELs integrated onto silicon by ultra-thin DVS-BCB adhesive bonding are presented. The hybrid-cavity implies that the optical field extends over both the GaAs- and the Si-based parts, which could allow a fraction of the light in the vertical-cavity to be coupled into an in-plane waveguide. Surface-emitting devices are demonstrated at ~860 nm with up to 2.3 mW optical output power and 12 GHz modulation bandwidth, providing error-free large signal data transmission up to 25 Gb/s.

1. Introduction

An efficient integrated short-wavelength light source on silicon would be a technological enabler for applications in life sciences, bio-photonics, and optical interconnects. An attractive route is the heterogeneous integration of a GaAs-based “half-VCSEL” onto a silicon-based reflector. This forms a hybrid-cavity, implying that the standing-wave optical field extends over both the GaAs- and the silicon-based parts. This concept has previously been pursued at longer wavelengths using InP-based materials [1], [2]. The hybrid-cavity allows for coupling a fraction of the light in the resonator to an in-plane waveguide [2], e.g. by using a weak diffraction grating [3], see Fig. 1(a).

As a step in this direction we have demonstrated surface-emitting VCSELs without the weak diffraction grating providing in-plane emission [4], see Fig. 1(b). By optimizing the bonding interface thickness between the “half-VCSEL” and the dielectric DBR, optical output powers up to 2.3 mW were achieved at room temperature [5].

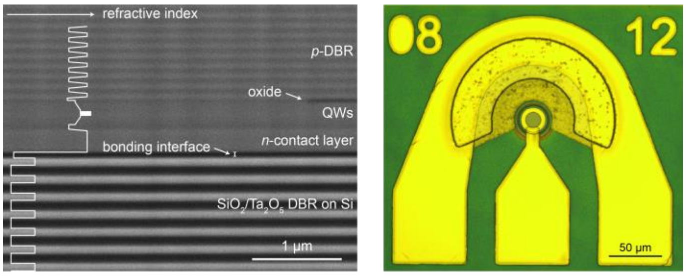


(a) (b)

Figure 1: Schematic cross-section of (a) hybrid vertical-cavity laser with in-plane emission, and (b) hybrid-cavity VCSEL.

2. VCSEL design and fabrication

The design and fabrication of the silicon-integrated hybrid-cavity VCSEL have been outlined in detail in [4]. In short, the GaAs-based “half-VCSEL” epitaxial structure contains an epitaxial *p*-AlGaAs DBR with a high-aluminum content layer for the formation of an aperture by selective wet oxidation, an intra-cavity *n*-contact layer, and an active region consisting of five strained InGaAs quantum wells. The bottom mirror is a SiO_2/Ta_2O_5 dielectric DBR deposited on silicon. The “half-VCSEL” structure was attached to the dielectric mirror using ultra-thin (40 nm) DVS-BCB adhesive bonding, followed by GaAs substrate removal. Devices were fabricated using standard processing steps for oxide-confined VCSELs. An SEM micrograph of a focused ion beam (FIB) cross-section and an optical micrograph of a fully fabricated VCSEL are shown in Fig. 2.



(a) (b)

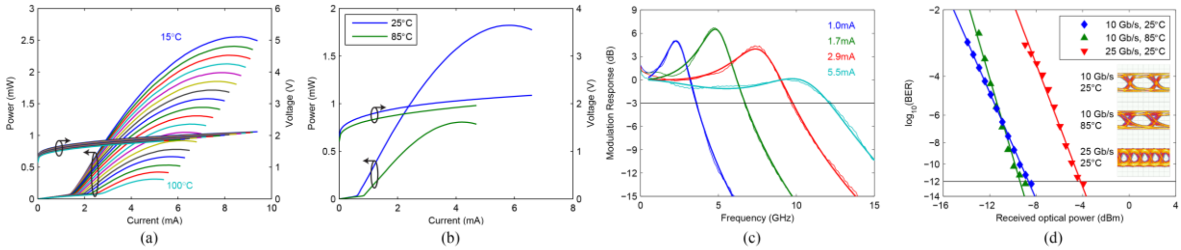
Figure 2: Fully fabricated hybrid-cavity VCSEL shown by (a) an SEM micrograph of a FIB cross-section, and (b) an optical micrograph of the chip surface.

3. Measurements

The light-current-voltage characteristics measured at ambient temperatures ranging from 15 to 100°C in steps of 5°C for a 10-µm oxide-aperture diameter silicon-integrated hybrid-cavity VCSEL with emission wavelength at ~860 nm are shown in Fig 3(a). This emission wavelength and the corresponding bonding interface thickness was chosen to obtain good performance at both room temperature and elevated temperatures [5]. The maximum output power is 2.3 mW (0.7 mW) at 25°C (85°C).

As the maximum power is limited by an early thermal rollover caused by the high thermal impedance bottom dielectric DBR, the achievable photon density in the cavity is also limited. Since a high photon density is desirable for high-speed modulation, a smaller 5-µm oxide-aperture diameter device was used for the dynamic experiments as a smaller device is capable of reaching higher photon densities already at lower currents.

The optical output power for the 5-µm device vs. current is shown in Fig. 3(b), while the small-signal modulation response at a few bias currents is shown in Fig. 3(c). The maximum 3 dB modulation bandwidth of the 5-µm oxide-aperture hybrid-cavity VCSEL is 12 GHz. Finally, the large signal capabilities were evaluated with a PRBS7 test pattern. Error-free data transmission was achieved up to 25 Gb/s (10 Gb/s) at 25°C (85°C), see Fig. 3(d).



(a) (b) (c) (d)

Figure 3: (a) Optical power and voltage vs. current for a 10-µm oxide-aperture diameter hybrid-cavity VCSEL at ambient temperatures ranging from 15 to 100°C in steps of 5°C. (b) Optical power and voltage vs. current for a 5-µm oxide-aperture diameter VCSEL at 25°C and 85°C. (c) Small-signal modulation response at 25°C for a 5-µm aperture diameter VCSEL at indicated bias currents. (d) Bit error ratio (BER) vs. received optical power for a 5-µm device operating at 10 and 25 Gb/s at 25°C, and 10 Gb/s at 85°C. Insets: Corresponding eye diagrams.

4. Conclusions

A silicon-integrated short-wavelength hybrid-cavity VCSEL with up to 2.3 mW optical output power at 25°C is demonstrated. Using a smaller oxide-aperture VCSEL, up to 12 GHz modulation bandwidth is achieved at 25°C, which is enough to support error-free data transmission up to 25 Gb/s at 25°C and up to 10 Gb/s at 85°C. These results indicate that heterogeneous integration of a “half-VCSEL” may be a viable route towards an efficient integrated in-plane waveguide light source.

Acknowledgement

This project has received funding from the Swedish Foundation for Strategic Research (SSF), the FP7-ERC-InSpectra Advanced Grant, and the European Union’s Horizon 2020 research and innovation program under grant agreement No. 688519 (PIX4life).

5. References

[1] J. Ferrara, W. Yang, L. Zhu, P. Qiao, and C. J. Chang-Hasnain, “Heterogeneously integrated long-wavelength VCSEL using silicon high contrast grating on an SOI substrate,” *Opt. Express*, vol. 23, no. 3, pp. 2512–2523, Feb. 2015.

[2] G. C. Park, W. Xue, A. Taghizadeh, E. Semenova, K. Yvind, J. Mørk, and I.-S. Chung, “Hybrid vertical-cavity laser with lateral emission into a silicon waveguide,” *Laser Photon. Rev.*, vol. 9, no. 3, pp. L11–L15, May 2015.

[3] D. A. Louderback, G. W. Pickrell, H. C. Lin, M. A. Fish, J. J. Hindi, and P. S. Guilfoyle, “VCSELs with monolithic coupling to internal horizontal waveguides using integrated diffraction gratings,” *Electron. Lett.*, vol. 40, no. 17, pp. 1064–1065, Aug. 2004.

[4] E. P. Haglund, S. Kumari, P. Westbergh, J. S. Gustavsson, G. Roelkens, R. Baets, and A. Larsson, “Silicon-integrated short-wavelength hybrid-cavity VCSEL,” *Opt. Express*, vol. 23, no. 26, pp. 33634–33640, Dec. 2015.

[5] E. P. Haglund, S. Kumari, E. Haglund, J. S. Gustavsson, R. G. Baets, G. Roelkens, and A. Larsson, “Silicon-Integrated Hybrid-Cavity 850-nm VCSELs by Adhesive Bonding: Impact of Bonding Interface Thickness on Laser Performance,” *IEEE J. Sel. Top. Quantum Electron.*, vol. 23, no. 6, p. 1700109, 2017.