

Impact of Bonding Interface Thickness on the Performance of Silicon-Integrated Hybrid-Cavity VCSELs

Emanuel P. Haglund^{1,*}, Sulakshna Kumari^{2,3}, Erik Haglund¹, Johan S. Gustavsson¹,
Roel G. Baets^{2,3}, Gunther Roelkens^{2,3}, and Anders Larsson¹

¹Photonics Laboratory, Department of Microtechnology and Nanoscience,
Chalmers University of Technology, SE-412 96 Göteborg, Sweden

²Photonics Research Group, INTEC Department, Ghent University – IMEC, Belgium

³Center for Nano- and Biophotonics, Ghent University, Belgium

*emanuel.haglund@chalmers.se

Abstract: The dependence of the performance of short-wavelength silicon-integrated hybrid-cavity VCSELs on the thickness of the bonding interface used for the heterogeneous integration has been studied. Performance measures investigated include the emission wavelength, thermal impedance, and variation of threshold current and output power with temperature.

Keywords: Heterogeneous integration, semiconductor lasers, silicon photonics, vertical-cavity surface-emitting laser (VCSEL).

1. INTRODUCTION

The integration of an efficient short-wavelength laser on silicon would benefit applications such as life sciences, biophotonics, and optical interconnects. Heterogeneous integration of GaAs-based hybrid-cavity VCSELs, where a “half-VCSEL” is attached to a reflector on silicon, is an attractive route, as GaAs-based VCSELs have demonstrated power conversion efficiencies exceeding 60% [1], modulation bandwidths up to 30 GHz [2], data rates in excess of 70 Gb/s [3], and energy dissipation of less than 100 fJ/bit up to 50 Gb/s [2], [4].

Recently, we demonstrated heterogeneously integrated hybrid-cavity 850 nm VCSELs on silicon with an output power of 1.6 mW [5] and a modulation bandwidth sufficient for 20 Gb/s data transmission [6]. However, these hybrid-cavity VCSELs suffered from an early thermal rollover of the output power due to a positive gain-to-resonance detuning caused by a too thin bonding interface. Here, we present the results from an investigation of the impact of the bonding interface thickness on important performance parameters.

2. VCSEL DESIGN

The design and fabrication of our silicon-integrated hybrid-cavity VCSELs have been described in [5]. In short, a GaAs-based “half-VCSEL” epitaxial structure, with the room temperature gain peak at ~850 nm, is attached to a dielectric distributed Bragg reflector (DBR) on silicon using ultra-thin (40 nm) DVS-BCB adhesive bonding, followed by removal of the GaAs substrate and subsequent VCSEL processing. A schematic cross-section is shown in Fig. 1. With the thickness of the bonding interface (indicated in Fig. 1) having an impact on VCSEL performance, a thin layer of SiO₂ (having a refractive index similar to that of DVS-BCB) was deposited on the *n*-contact layer prior to bonding to adjust the effective bonding interface thickness. In this study the combined DVS-BCB and SiO₂ thickness was varied between ~40 and ~180 nm, corresponding to cavity resonance wavelengths from ~845 to ~865 nm. The performance of hybrid-cavity VCSELs with an oxide-aperture diameter of 10 μm and 4 different bonding interface thicknesses (denoted A–D) was investigated.

3. MEASUREMENTS

Room temperature (RT, 25°C) resonance wavelengths of 843.3, 852.5, 861.2, and 867.2 nm for VCSELs A–D, with increasing thickness of the bonding interface, were extracted from optical emission spectra recorded below threshold (0.5 mA). This corresponds to a gain-to-resonance detuning of approximately +7, –3, –11, and –17 nm, respectively. RT emission spectra above threshold (2 mA) are shown in Fig. 2.

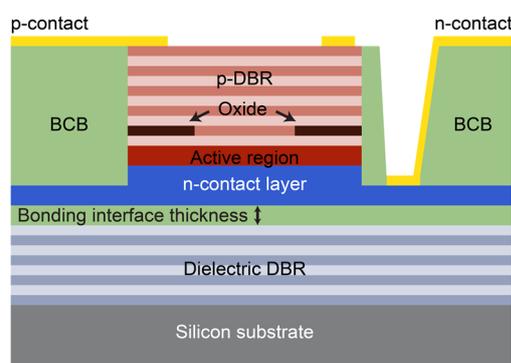


Fig. 1. Schematic cross-section of the silicon-integrated hybrid-cavity VCSEL, with the bonding interface thickness indicated.

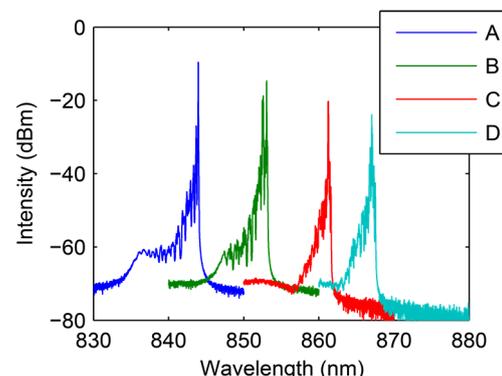


Fig. 2. Optical emission spectrum at 25°C for hybrid-cavity VCSELs A–D, with different bonding interface thicknesses, at 2 mA bias current.

Light-current-voltage characteristics measured at ambient temperatures from 15 to 100°C (in steps of 5°C) are shown in Fig. 3. At RT the threshold current is 1.42, 1.07, 1.48, and 1.85 mA for VCSELs A–D. By fitting a second order polynomial to the dependence of threshold current on temperature, the minimum threshold current is estimated at 6, 27, 36, and 54°C for VCSELs A–D (see Fig. 4), where the corresponding threshold current is 1.3, 1.1, 1.4, and 1.6 mA, respectively. The maximum optical output power at RT is 2.3 mW, delivered by VCSEL B, whereas the maximum optical output power at 100°C is 0.58 mW, delivered by VCSEL D. The maximum operating temperature for VCSEL A is 70°C. Also, with the largest negative detuning (VCSEL D), there is a very small variation of the threshold current with temperature. The thickness of the bonding interface can therefore be conveniently chosen for either minimum threshold current or maximum output power at a given temperature or for a minimum of variation of threshold current with temperature.

A relatively high thermal impedance of ~ 7 K/mW was measured for all four VCSELs, irrespective of the bonding interface thickness. The thermal impedance is thus dominated by the limited heat-transport through the dielectric DBR to the silicon substrate.

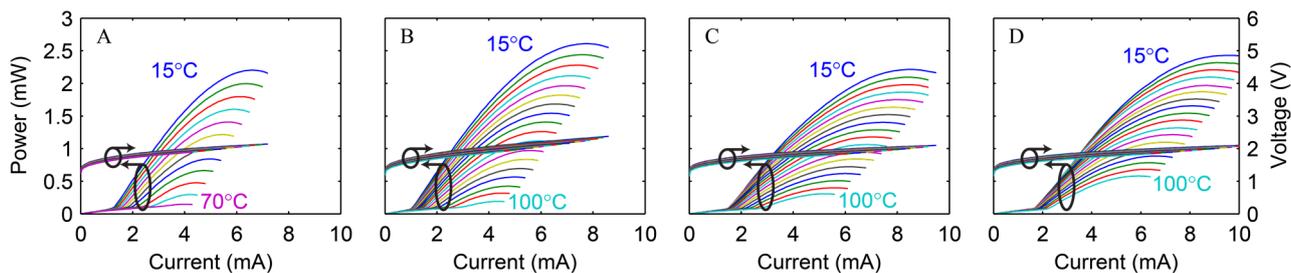


Fig. 3. Light-current-voltage characteristics for hybrid-cavity VCSELs A–D with resonance wavelengths at 843.3, 852.5, 861.2, and 867.2 nm measured at ambient temperatures from 15 to 100°C in steps of 5°C.

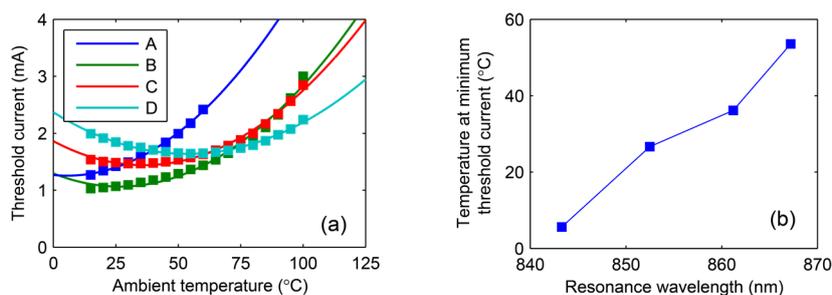


Fig. 4. (a) Threshold current of hybrid-cavity VCSELs A–D versus ambient temperature and (b) temperature at minimum threshold current versus resonance wavelength.

4. CONCLUSION

The dependence of the performance of silicon-integrated hybrid-cavity VCSELs on the thickness of the bonding interface has been mapped. The thickness can be used to control important performance measures such as threshold current and output power and their dependencies on temperature.

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).

REFERENCES

- [1] K. Takaki, N. Iwa, K. Hiraiwa, S. Imai, H. Shimizu, T. Kageyama, Y. Kawakita, N. Tsukiji, and A. Kasukawa, "A recorded 62% PCE and low series and thermal resistance VCSEL with a double intra-cavity structure," in *IEEE International Semiconductor Laser Conference*, 2008, post deadline paper PDP1.
- [2] E. Haglund, P. Westbergh, J. S. Gustavsson, E. P. Haglund, A. Larsson, M. Geen, and A. Joel, "30 GHz bandwidth 850 nm VCSEL with sub-100 fJ/bit energy dissipation at 25–50 Gbit/s," *Electron. Lett.*, vol. 51, no. 14, pp. 1096–1098, July 2015.
- [3] D. M. Kuchta, A. V. Rylyakov, F. E. Doany, C. L. Schow, J. E. Proesel, C. W. Baks, P. Westbergh, J. S. Gustavsson, and A. Larsson, "A 71-Gb/s NRZ modulated 850-nm VCSEL-based optical link," *IEEE Photonics Technol. Lett.*, vol. 27, no. 6, pp. 577–580, March 2015.
- [4] P. Moser, J. A. Lott, P. Wolf, G. Larisch, H. Li, N. N. Ledentsov, and D. Bimberg, "56 fJ dissipated energy per bit of oxide-confined 850 nm VCSELs operating at 25 Gbit/s," *Electron. Lett.*, vol. 48, no. 20, pp. 1292–1294, Sept. 2012.
- [5] 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.
- [6] E. P. Haglund, S. Kumari, P. Westbergh, J. S. Gustavsson, R. G. Baets, G. Roelkens, and A. Larsson, "20-Gb/s modulation of silicon-integrated short-wavelength hybrid-cavity VCSELs," *IEEE Photonics Technol. Lett.*, vol. 28, no. 8, pp. 856–859, April 2016.