

EMPOWERING SILICON WITH VERTICAL-CAVITY LASERS

Bringing the advantages of the VCSEL to silicon photonics with vertical-cavity lasers

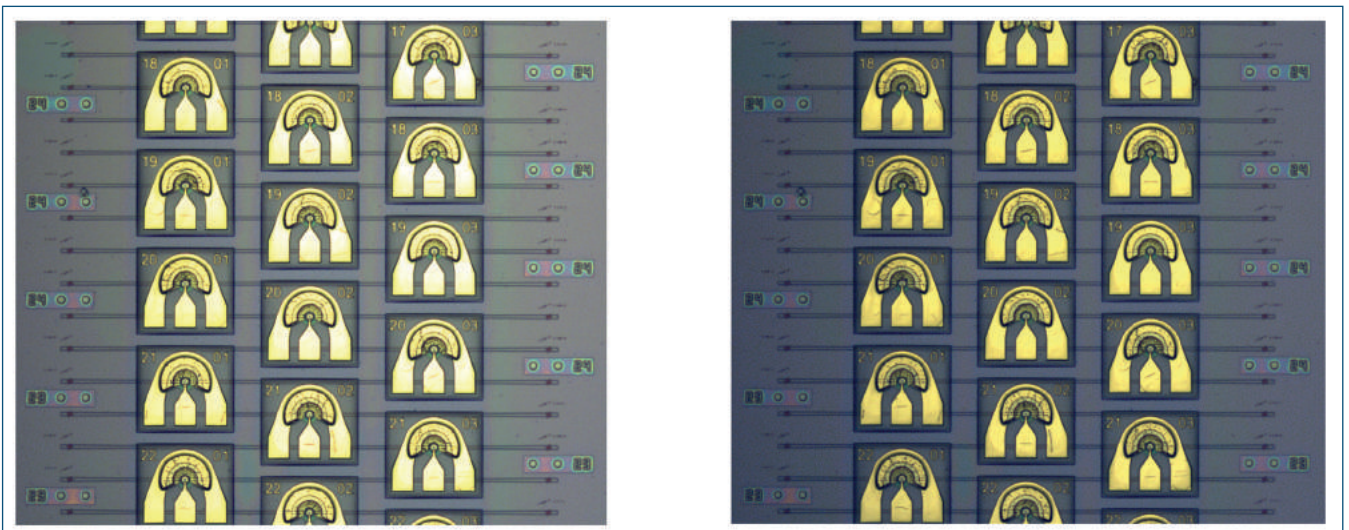
BY ANDERS LARSSON, EMANUEL HAGLUND AND JOHAN GUSTAVSSON FROM CHALMERS UNIVERSITY OF TECHNOLOGY, GÖTEBORG, AND SULAKSHNA KUMARI, GUNTHER ROELKENS, AND ROEL BAETS FROM GHENT UNIVERSITY-IMEC

PHOTONIC INTEGRATED CIRCUITS (PICs) have many merits. Their attributes include a high degree of functionality, a capability to realise a great deal of complexity, a small footprint and a low cost.

The two leading platforms for the production of PICs are InP and silicon. The primary advantage of the former – predominantly used in transceivers for wavelength division multiplexed telecom systems – is the monolithic integration, on a single chip, of all active and passive elements, including lasers as light sources. In contrast, the latter – commonly referred to as silicon photonics – has the advantage of a far

lower propagation loss in the waveguide. With this material system, there is the benefit of the use of CMOS fabrication processes, which are suited to high-volume, low-cost manufacturing.

Waveguides for silicon photonics are often made from silicon or SiN. Silicon is transparent at wavelengths beyond 1.1 μm , so this technology, which is based on silicon-on-insulator structures, is the most common platform for telecom and datacom transceivers. If transparency in the visible range or near-infrared (below 1.1 μm) range is required, silicon is unsuitable, and SiN waveguides tend to be adopted. SiN



Arrays of hybrid vertical-cavity lasers with intra-cavity SiN waveguides

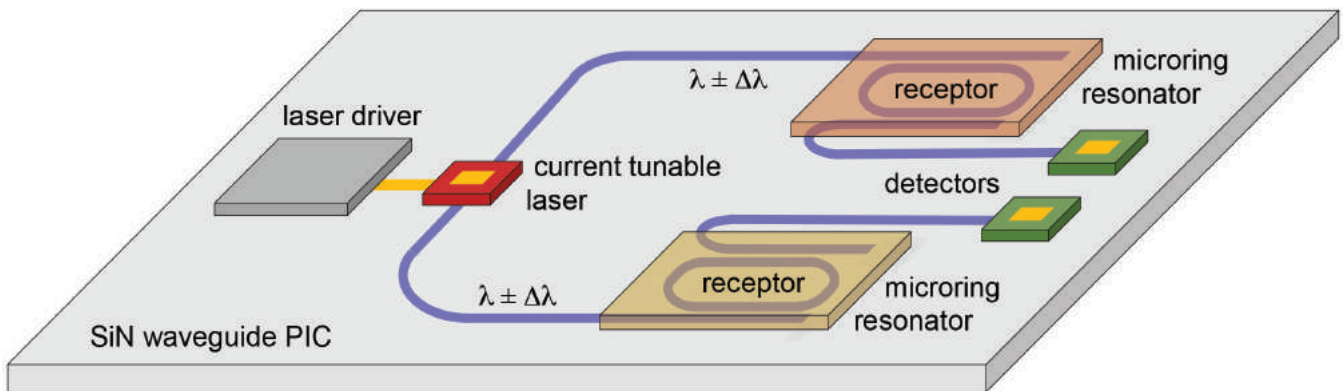


Figure 1. A bio-photonic SiN PIC sensor chip with integrated micro-ring resonators coated by receptor layers, a heterogeneously integrated current tuneable laser, and flip-chip integrated laser driver and grating coupled photodetectors.

technology is often used to fabricate PICs for bio-photonics and life sciences, where wavelengths in the visible and very-near-infrared are of particular interest.

One major challenges for any PIC made with silicon photonics is the integration of the light source. Difficulties arise from the lack of a direct bandgap for silicon and its compatible compounds, such as SiGe and SiN. A direct bandgap material is essential, as it is a prerequisite for efficient light generation and amplification.

Most of the producers of silicon PICs select one of three approaches to integrate the lasers to the chips. Their least mature option is monolithic integration, which involves hetero-epitaxial growth of compound semiconductors on to silicon. One alternative is heterogeneous integration, which involves attaching epitaxial compound semiconductor structures to silicon using either die or wafer bonding. The resulting structure is processed to form lasers, allowing the merger of otherwise incompatible materials to yield a high-performance laser. There is also a third

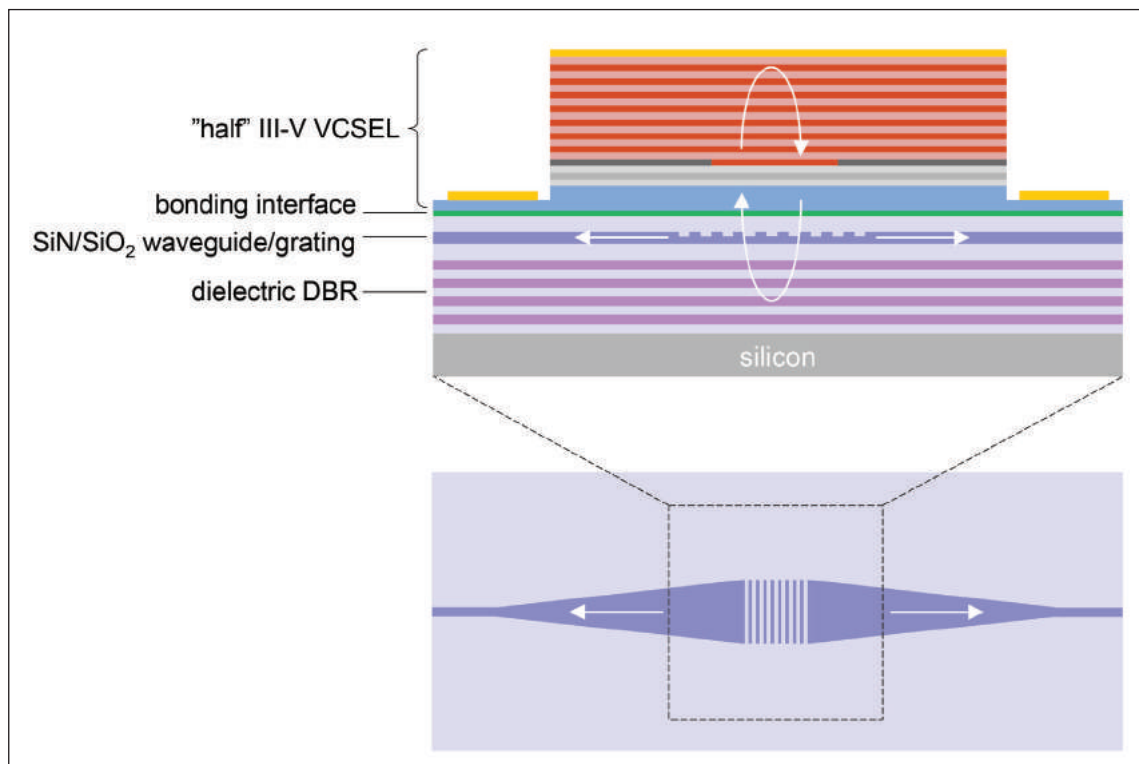


Figure 2. The concept of hybrid vertical-cavity laser integration on SiN PICs. Upper: Cross-sectional view of the 'half III-V VCSEL' bonded to a dielectric DBR on silicon with an intra-cavity SiN waveguide with a weak diffraction grating on top. During each round-trip in the vertical cavity, a certain fraction of the photons stored in the cavity is tapped off to the in-plane intra-cavity waveguide. Lower: Top view of the SiN waveguide and grating onto which the 'half III-V VCSEL' is bonded.

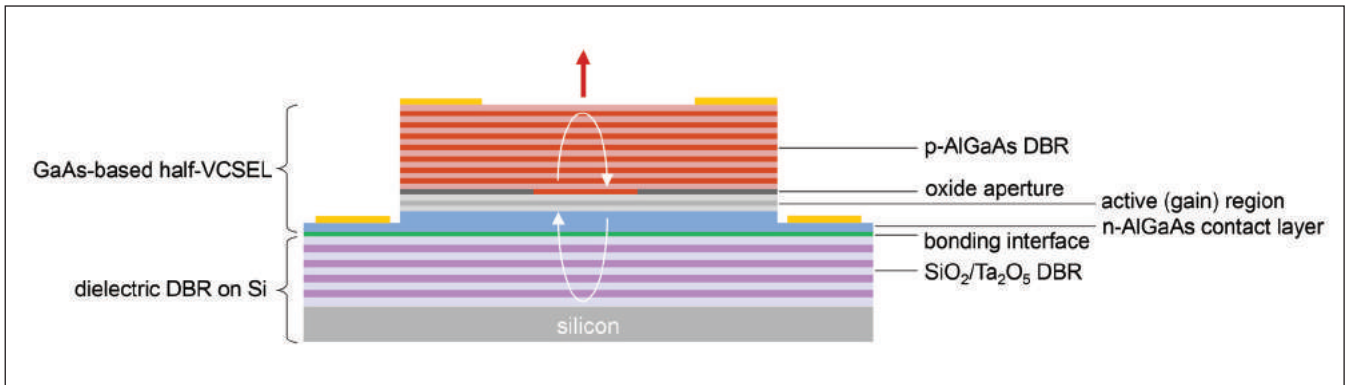


Figure 3. The GaAs-based surface-emitting version of the hybrid vertical-cavity laser, lacking the intra-cavity SiN waveguide and grating for in-plane emission.

approach: hybrid integration. In this case, light from a stand-alone laser is coupled to the on-chip silicon or SiN waveguide.

Regardless of the approach, most engineers incorporate an in-plane laser in their PIC. However, its performance is not ideal: it has high bias and modulation currents, it operates with a low power conversion efficiency, and it has a large footprint.

VCSEL virtues

For data communication, sensing and some high-power applications, the most common laser used today is not an in-plane device, but a VCSEL. Its success stems from: its small optical mode and gain volumes, enabling efficient operation and high-speed modulation at low currents; and its vertical geometry, which provides surface emission and enables dense two-dimensional arrays and low-cost fabrication and testing.

The success of VCSELs raises an obvious question: can it, or a device like it, provide the light sources for silicon photonics? If it could, it would empower silicon photonics with a class of lasers that offer a low current, a high efficiency and a small footprint.

Given all this promise, it is of no surprise that many

groups have tried to develop silicon PICs that feature flip-chip integration of long-wavelength (InP-based) and short-wavelength (GaAs-based) VCSELs over optical coupling elements, such as gratings and mirrors. However, this approach does not deliver a wafer-scale process. Instead, it involves accurate, time-consuming alignment of individual VCSELs in a back-end process.

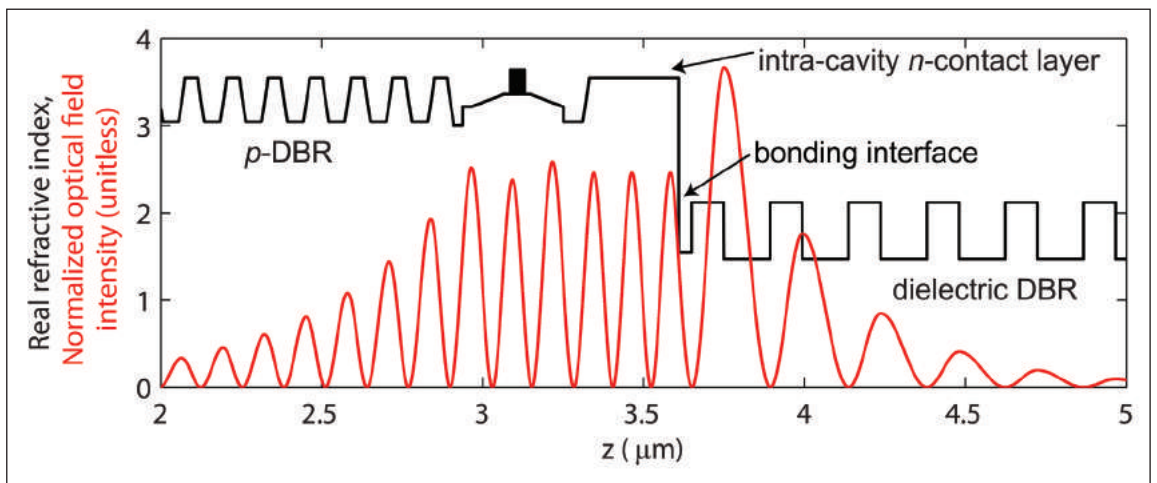
What's needed is a wafer-scale compatible process. Fulfilling this goal is our partnership between researchers at Chalmers University of Technology and Ghent University-imec. Together we have developed a process for the heterogeneous integration of hybrid vertical-cavity lasers.

At the heart of our technology is the formation of a hybrid vertical-cavity laser via the bonding of an epitaxial III-V structure – it contains the upper reflector and an active region that provides optical gain under current injection – to a lower reflector on the silicon substrate. This approach forms a hybrid vertical cavity.

With our technology, light is coupled to an in-plane silicon or SiN waveguide with an optical element in the cavity. This element taps off power to the waveguide.

Our technology is applicable to many material

Figure 4. Optical field intensity and refractive index along the optical axis of the hybrid vertical-cavity laser.



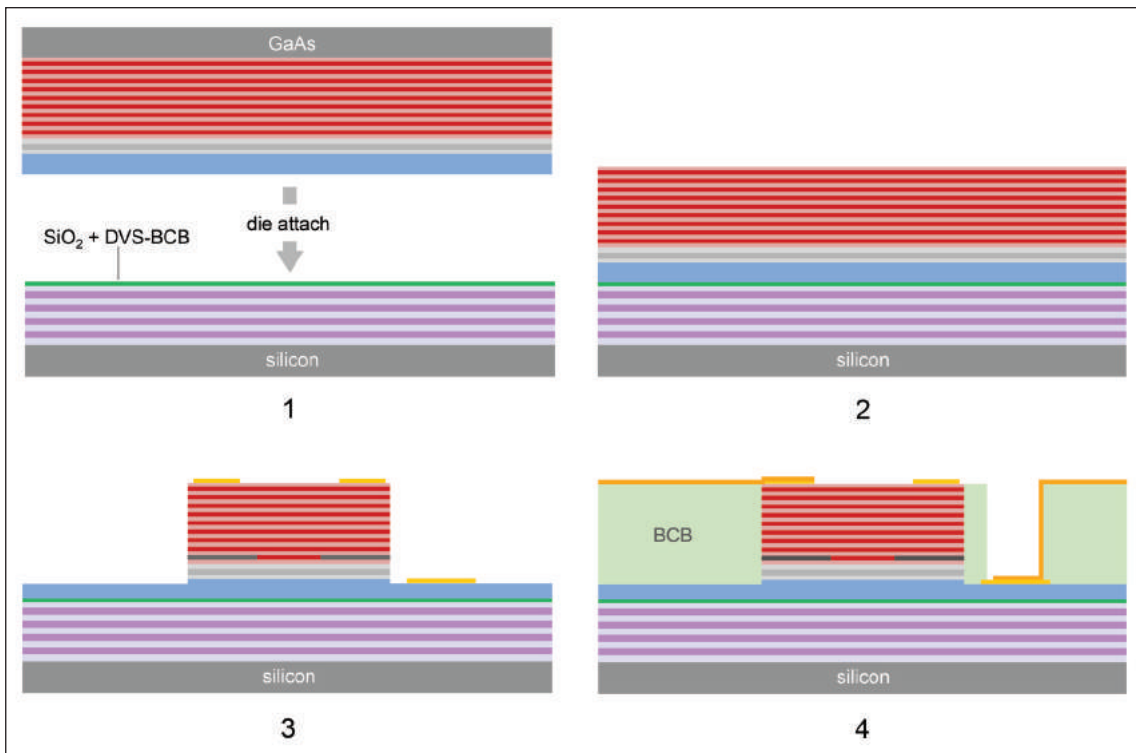


Figure 5. Illustration of the fabrication process for the GaAs-based hybrid vertical-cavity laser. (1) Bonding of III-V die on the silicon part using adhesive bonding. (2) Removal of the GaAs substrate. (3) Top contact metallization, mesa etching, selective oxidation, and bottom contact metallization. (4) Planarization with BCB and deposition of pad metals.

systems. It is compatible with GaAs, InP, and GaSb-based materials, for emission in the very-near-infrared, near-infrared, and mid-infrared, respectively; and with the development of GaN-based materials, it may become useful for visible light sources.

We are not the only team pursuing this type of approach. However, we distinguish ourselves by working with GaAs-based materials and targeting light source integration for the very-near-infrared. Meanwhile our peers, the group of Connie Chang-Hasnain at the University of California at Berkeley and the group of Il-Sug Chung at the Technical University of Denmark, use InP-based materials as near-infrared sources.

The GaAs-based, hybrid vertical-cavity laser technology that we are developing forms part of the European Horizon 2020 project PIX4life. The project, co-ordinated by imec and involving 15 partners across Europe, aims to establish a SiN PIC pilot-line for life science applications in the visible and very-near-infrared. An intended outcome of our efforts is a line that will aid product development for a broad range of industrial customers.

One example of a device developed on this line is a bio-photonic sensor (see Figure 1). This chip contains micro-ring resonators coated by receptors. The receptors selectively bind target analytes, leading to a shift in the micro-ring resonance frequency. Sensing

these shifts is an on-chip current tuneable laser, which interrogates multiple sensors with different receptors. For this kind of sensing PIC, the hybrid vertical-cavity laser is potentially the ideal light source.

To enable on-chip integration of hybrid vertical-cavity lasers, we are developing an integration platform that features a dielectric distributed Bragg reflector (DBR) buried under the waveguide on the silicon substrate (see Figure 2). We accomplish this by bonding the epitaxial structure with the upper DBR and the active region to the silicon wafer to form the hybrid vertical-cavity. A shallow grating etched in the intra-cavity waveguide diffracts light to the in-plane waveguide. Note that an additional benefit of the buried DBR is that it can improve the efficiency of grating couplers used to couple light from the PIC into the likes of optical fibres or flip-chip integrated detectors.

Surface-emitting lasers

An ultimate goal of our project is to demonstrate on-chip waveguide-coupled integration of hybrid vertical-cavity lasers. However, we begin by taking a step towards this: a surface-emitting version, which is a VCSEL. By taking this route, we can develop and implement the integration architecture, and then investigate its performance characteristics and limitations.

Our intermediate structure features a SiO₂/Ta₂O₅ DBR

on silicon for the lower reflector, on which we bond a GaAs-based epitaxial structure with a *p*-type AlGaAs DBR, an active region with strained InGaAs quantum wells, and an intra-cavity *n*-type AlGaAs contact layer (see Figure 3). As is often the case for GaAs-based VCSELs, we use selective oxidation to form an oxide aperture for transverse current and optical confinement.

We have designed our hybrid vertical-cavity laser for 850 nm emission. With the design we are pursuing, the optical field extends over the GaAs-based and silicon-based parts of the hybrid cavity (see Figure 4).

Fabrication of our developmental structure begins with the preparation of its two parts (see Figure 5). They are formed by depositing the dielectric DBR on the silicon wafer and growing the epitaxial structure on the GaAs substrate by MOCVD. An additional thin layer of SiO₂ is deposited on the dielectric DBR, followed by spin-coating a film of the polymer DVS-BCB, which acts as an agent for adhesive bonding.

With our approach, the thickness of the bonding interface is defined by the combined thicknesses of the SiO₂ layer and the polymer. The polymer thickness is fixed at 40 nm, while the thickness of the SiO₂ layer is varied to control the interface thickness. Careful control of the thickness of the bonding layer is crucial, because it determines the length of the resonator and thus the emission wavelength.

After this step, dies of the GaAs-based epi-structure are bonded to the dielectric DBR on silicon, before the GaAs substrate is removed. Standard fabrication techniques for oxide-confined VCSELs are then employed, including mesa etching down to the intra-cavity contact layer, selective oxidation, and deposition of contact and pad metals. To cut capacitance,

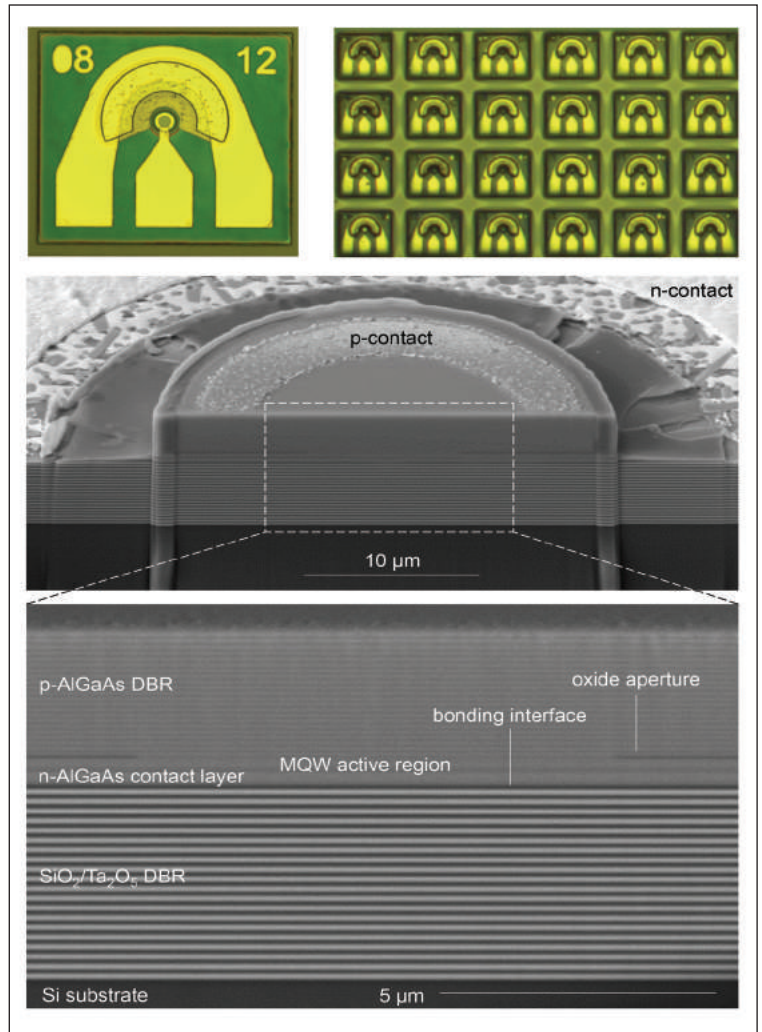


Figure 6. Upper: Optical microscope images of a single hybrid vertical-cavity laser and an array of such lasers. Lower: Scanning electron microscope images of a focused ion beam cross-section through the hybrid vertical-cavity laser (before BCB planarization).

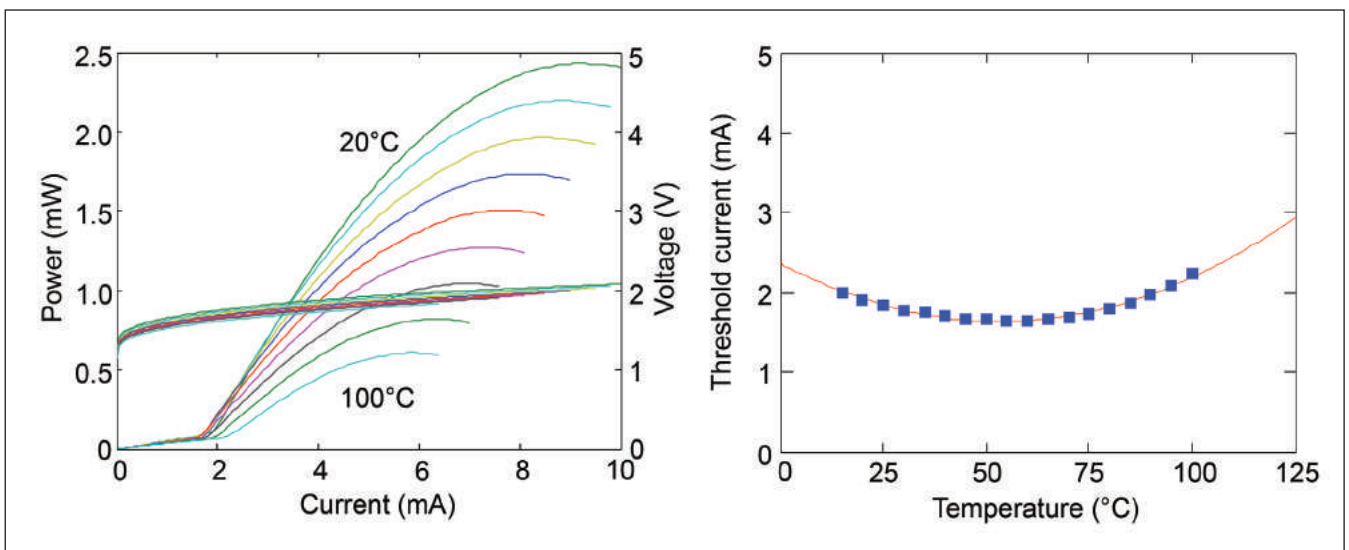


Figure 7. Left: Output power and voltage as a function of drive current at temperatures from 20°C to 100°C for an 850 nm hybrid vertical-cavity laser with an oxide aperture diameter of 10 μm. Right: Dependence of threshold current on temperature.

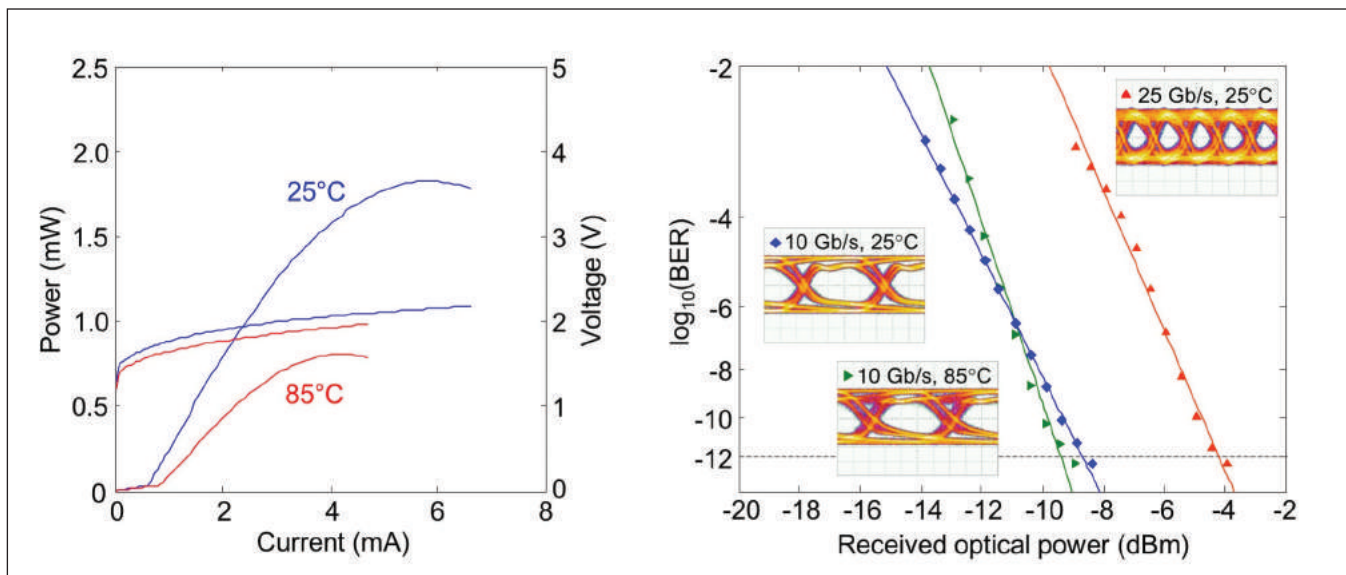


Figure 8. Left: Output power and voltage as a function of drive current at 25°C to 85°C for an 850 nm hybrid vertical-cavity laser with an oxide aperture diameter of 5 μm . Right: Results from data transmission experiments at 10 Gbit/s up to 85°C and 25 Gbit/s at 25°C.

necessary for investigating high-speed modulation capabilities, we planarized the structure with BCB. To study the uniformity of the bonding interface, we expose a cross-section through the hybrid vertical-cavity laser with a focused ion beam. The image that results allows identification of all parts of the laser, and reveals that the interface is highly uniform (see Figure 6).

Basic performance characteristics are obtained by measuring the optical output power and voltage as a function of current at temperatures up to 100°C. Plots show that performance, evaluated in terms of the temperature-dependent threshold current and slope efficiency (see Figure 7(a)), is similar to that of an ordinary oxide-confined VCSEL. This demonstrates the potential of our approach to integration.

We have found that if an appropriate thickness is used for the bonding interface, the threshold current is only weakly dependent on temperature (see Figure 7(b)). However, the output power saturates at relatively low currents, due to the high thermal impedance - it stems from the low thermal conductivity of the dielectric DBR. One way to address this is to integrate metallic heat spreaders or thermal shunts. These modifications increase the efficiency that heat is conducted to the silicon substrate, leading to reduced thermal impedance and ultimately a higher output power.

Another promising application for our short-wavelength, hybrid vertical-cavity laser is as the light source in integrated transmitters for wavelength division multiplexed optical interconnects, where the SiN PIC is used for multiplexing. To evaluate its potential, we have studied the dynamics, measuring the modulation bandwidth and data transmission rates. We found that we could transmit data at up to

25 Gbit/s at room temperature and 10 Gbit/s at 85°C by using a smaller aperture and a modulation bandwidth exceeding 10 GHz (see Figure 8).

Our results showcase the potential of our hybrid vertical-cavity laser for the integration of low-current, high-efficiency, small-footprint light sources on silicon PICs. However, there is still work to do. We must demonstrate that a similar performance is possible with in-plane emission, by incorporating an intra-cavity waveguide and diffraction grating. The good news is that the signs are promising, with simulations suggesting that the lower waveguide/grating/DBR combination can be designed to pin the polarization of the cavity mode in the direction needed for controlled, efficient coupling to the waveguide.

• The authors would like to acknowledge the financial support from the European Union's Horizon 2020 research and innovation program under grant agreement number 688519 (PIX4life), the Swedish Foundation for Strategic Research (SSF), and the FP7-ERC-InSpectra Advanced Grant.

Further reading

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