Facet-coupled heterogeneous integration of GaAs SOAs on silicon nitride through micro-transfer printing for near-visible applications

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Integrated Silicon Nitride (SiN) photonic circuits offer high flexibility, low losses, and a wider wavelength operating range compared to silicon-based waveguides. The possibility to use wavelengths down to less than 800 nm can enable applications such as Optical Coherence Tomography and fully integrated optical Rubidium clocks. Central to this promise is the integration of (low-linewidth) laser sources operating in these shorter wavelength ranges. By integrating Gallium-Arsenide (GaAs) semiconductor optical amplifiers (SOAs) on the low-loss platform SiN, ultra-narrow linewidth extended-cavity lasers can be created on a fully integrated platform. However, the integration of GaAs with SiN has shown to be challenging due to the high refractive index mismatch between the two materials, making evanescent coupling practically impossible. This work proposes a novel facet-coupling based approach to integrating GaAs SOAs operating at 780 nm on a SiN platform using micro-transfer printing into an etched recess. By optimizing the spatial overlap of the SOA mode with the SiN mode, direct non-adiabatic broad-band facet coupling can be achieved with simulated theoretical coupling between III-V and SiN of up to 72%. This works shows the integration method, as well as the simulations of the coupling between the SOA and the waveguide platform.

Introduction

In the past years, a great push has been made to extend integrated photonics to the shorter wavelength spectrum. While silicon-based infrared and mid-infrared photonics have offered many technical solutions, most notably in telecom/datacom fields, many fully integrated sensing applications requiring visible wavelengths have been firmly out of reach due to the relatively narrow bandgap of silicon. At a wavelength of 800 nm, optical coherence tomography and fully integrated optical Rubidium clocks are two of the main envisioned applications for photonics. To accommodate such wavelengths, Silicon Nitride (SiN) based waveguides are used, offering transparency well through the visible spectrum. Central to these sensing solutions is the integration of a narrow-linewidth laser on the silicon nitride platform. Since silicon nitride is a passive dielectric, gain at these wavelengths must come from the heterogenous integration of III-V materials, most notably Gallium Arsenide (GaAs) semiconductor optical amplifiers (SOAs) at 800 nm.

Unfortunately, the integration of GaAs on SiN is difficult, mostly due to the mismatch in refractive index, making direct evanescent coupling impossible. Most commonly, III-V materials are integrated on top of patterned SiN wafers through (die-to-)wafer bonding or micro-transfer printing and coupled using evanescent fields [1, 2]. To couple from the high-index III-V materials to the low-index SiN, an intermediate layer with a taper is generally used. For mid-IR, coupling between Indium Phosphide integrated on SiN using micro-transfer printing has been frequently demonstrated using an amorphous silicon intermediate layer. However, selection of such layers for sub-micron wavelengths is much more difficult. In other recent work, integration of bonded GaAs on SiN was shown using an intermediate dielectric coupling structure that is butt-coupled to the GaAs SOA and evanescently coupled to the SiN [3].

This work proposes instead to forgo the coupling structure and directly butt-couple the SOA to the SiN waveguide. This is made possible by using the flexible micro-transfer printing approach, which can print a small fully pre-fabricated structure into a recess, allowing for vertical alignment of the SOA and waveguide modes. In this paper, the fabrication approach for butt-coupling through micro-transfer printing is laid out and verified through simulations, showing more than 70% maximum coupling efficiency. Furthermore, it shows that, within reasonable alignment tolerances, more than 50% theoretical coupling efficiency is possible.

Device integration procedure

The GaAs SOAs are designed as edge-coupled devices. To this end, both ends of the SOA are dry-etched to form facets. On the back-side of the SOA, the facet is straight and coated with a layer of gold to form a broad-band mirror. The front-side facet is used to couple to the SiN waveguide and is etched at an angle to prevent reflections into guided modes. The SOAs are designed to be heterogeneously integrated on a SiN-on-oxide feedback chip to form low-noise extended-cavity lasers, as shown in Figure 1(a). Here, an example design is pictured of a Fabry-Perot-type extended-cavity laser using the SOA, a taper for matching the mode shapes of the SOA and SiN modes for butt-coupling, a SiN waveguide spiral, and a narrow-band Bragg reflector.

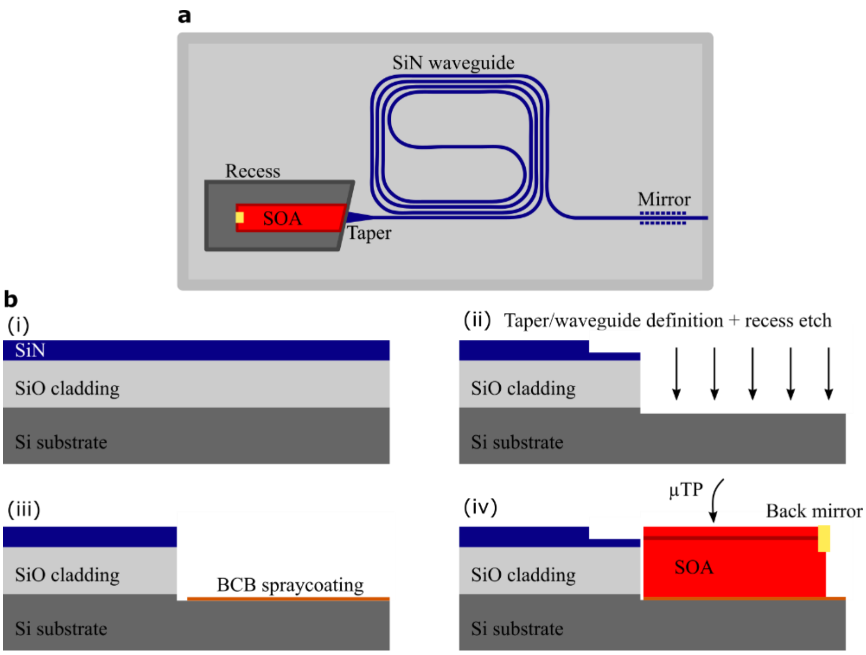

Figure 1: a) example of an heterogeneously integrated extended-cavity laser with a micro-transfer printed SOA in a recess, a SiN waveguide spiral, and a narrow-band Bragg grating. b) fabrication steps for SOA integration showing (i) unprocessed target wafer, (ii) taper/waveguide definition and recess etching, (iii) BCB bonding layer spray-coating and patterning, and (iv) micro-transfer printing of SOA into the recess using a polymer stamp.

The SOAs are coupled to the SiN feedback chip by micro-transfer printing them. Here, fully-processed SOA's are transferred into an etched recess, thereby aligning the SOA mode with the SiN both horizontally and vertically. This shows the relative flexibility of the micro-transfer printing approach. The complete process flow for integration is shown in Figure 1(b). First, the waveguides are etched in the SiN, as well as the taper. To align the SOA mode with the SiN waveguide mode vertically, a recess is etched in the target chip. Since the (usually positive) slope of the sidewall of this recess will determine the minimum distance between the SOA facet and the SiN facet, the sidewall should be as straight as possible. Subsequently, a polymer bonding layer of benzocyclobutene (BCB) is spray-coated and patterned so it only covers the recess floor. This patterning can also allow to remove any sloping of the BCB up to the recess sidewall, which would complicate the transfer-printing alignment. Next, the pre-fabricated SOA is printed in the recess. Lastly, the whole chip can be cladded in oxide or BCB to further reduce reflections and the chip is metallized to form electrical contacts for the SOA.

The horizontal alignment is done using the transfer printer. Since the height of the quantum wells and thus the optical mode in the SOA is known very precisely, the depth of the recess can be made to match this to vertically align the SOA. Since the SOA is placed in a recess, it can be directly placed on the silicon (Si) substrate. In other methods, the SOA is always placed above the SiN and SiO layers, the latter insulates heat very well. This means this method provides much better heat sinking of the SOA to the Si substrate. Since heat generation is usually the main factor limiting with how much current a heterogeneously integrated laser can be pumped, this will allow for higher pump currents and thus laser output power.

Alignment simulations

The most important consideration for the direct butt-coupling approach is the alignment tolerance. To verify the potential of this approach, therefore, finite-difference time domain (FDTD) simulations were performed using Lumerical's software suite. From optical mode simulations, the ideal cross-section for the SiN taper end was found to be 3000 nm by 80 nm, resulting in a mode overlap of 95% with the SOA mode, which is shown in Figure 2(a). This geometry was then used in an FDTD simulation to find the coupling efficiency between the two geometries for different misalignments. The optical propagation from the SOA to the SiN is plotted in Figure 2(b). To reduce reflections within the laser cavity, the GaAs waveguide is angled by 7 degrees and the SiN by the corresponding optimal angle following from Snell's law. Furthermore, a layer of SiN is present on the GaAs facet. This layer is an inherent product of the fabrication method of the SOA and can be tuned to form a simple anti-reflective (AR) coating.

The ideal case, where the SOA is printed directly against the recess edge, is plotted in Figure 2(c). However, in practice, this is very hard to realize. In work by Juvert et al. [4], coupons were shown to be printed within 1 µm of the recess edge and mostly within a 1 µm spread in lateral misalignment. In Figure 2(d), the coupling values for a facet distance of 1 µm are therefore plotted. Clearly, within these misalignment values, theoretical coupling values in excess of 50% can be expected, showing the feasibility of this integration method.

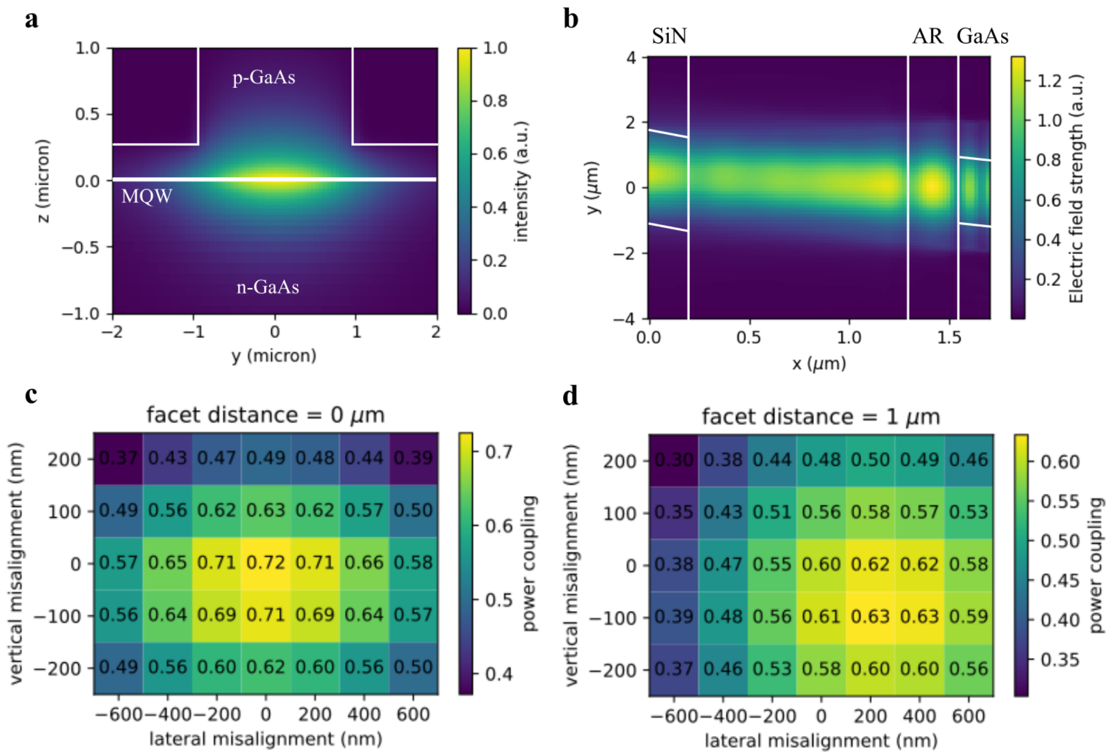

Figure 2: a) Optical mode of the GaAs SOA with outlines for the multiple quantum wells (MQW) and the ridge waveguide. b) Top-down view of the optical propagation from the GaAs to the SiN with outlines for the SiN waveguide and GaAs ridge, as well as the SiN AR coating. c) Power coupling heat map for a facet distance of 0 µm (ideal case) for different alignments. d) Power coupling values for a facet distance of 1 µm (realistic case).

Conclusions

In conclusion, we demonstrate a novel coupling method for GaAs on SiN heterogeneously integrated lasers, using direct facet-coupling of GaAs SOAs micro-transfer printed in a recess. Here, we outline the integration method and show FDTD coupling simulations for misalignment in three dimensions, showing larger than 50% coupling efficiencies for realistic misalignment values. This method may allow for easier integration of GaAs on the SiN platform, allowing for applications such as OCT and Rubidium optical clocks.

References

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