Micro-transfer printing for the heterogeneous integration of single-photon sources on SiN

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1 Introduction

Many different technological platforms for quantum information processing are currently under study. Depending on the application some clear distinctions can already be made. Especially for quantum communication, photonics seems to be a promising candidate.

Single-photon sources can create mobile quantum states but applications typically have tremendous requirements such as $> 80\%$ transmission losses from source to detector while maintaining high purity and visibility from the single photon state. Nowadays, performance for the latter of up to 96% and 99.4% respectively is found for epitaxially grown InAs[1] and InGaAs[2] quantum dots embedded in a GaAs platform. Best coupling performance is found for microcavities that outcouple directly to a fiber, but the coupling losses of several discrete optical components grows very quickly. This means, all-integrated solutions are preferred for quantum photonic experiments. In other work[1], emitted single photons are coupled to photonic crystal cavities or waveguides in the plane with coupling factors β possibly exceeding 90% allowing for on-chip experiments. Unfortunately, this GaAs platform suffers great scattering losses on the order of 10 dB/mm. As a result, no single material platform allows for the low-loss operation of state-of-the-art single photon sources.

2 Heterogeneous integration

Heterogeneous integration techniques can overcome this bottleneck for quantum hardware. It offers the possibility of directly integrating such high-performing devices on top of low loss silicon photonics platforms. For this work, we focus on a SiN interposer since the material is known to be transparent and extremely low loss at the operating near infrared wavelengths.

In previous work[3, 4], wafer or die bonding has already been studied to realize such GaAs-on-SiN material stacks. For this integration method, entire GaAs dies are bonded on SiN with a considerable spacing layer prior to patterning of the devices. This way, antibunching experiments have been realized. In order to improve scalability and efficient use of source material as well as to reduce back-end processing, also pick-and-place methods have been studied[5]. In the work of this paper however, we focus on micro-transfer printing which extends upon pick-and-place methods with a commercially available tool that allows scaling to high-throughput printing. It allows printing of standalone GaAs nanobeam waveguides that are tapered from both sides to allow mode coupling to the underlying SiN interposer. The nanobeam GaAs waveguides involved are only 300 nm wide and 160 nm thick to allow for high-efficiency waveguide coupling of the quantum dot emission. Printing devices of such reduced dimensions posed new challenges compared to previous micro-transfer printing work such as for III-V lasers or photodiodes[6].

3 Mode coupler design

Apart from the fabrication process, also the mode coupling is very different for GaAs nanobeams as compared to e.g. III-V amplifier sections of much greater thicknesses. Because of the large index contrast with SiN and the large waveguide dimensions, this usually required an intermediate high-index layer to improve coupling[7]. That deemes unnecessary for the case of nanobeam waveguides of reduced thickness. In this section, this micro-transfer printed mode coupler is designed which is of tremendous importance here given the high requirement on transmission efficiency. Although most-recent micro-transfer printing tools can guarantee a 200 nm lateral misalignment (3σ), typical commercial tools such as the one used in this work are still limited to around 500 nm of misalignment[8]. To alleviate this issue, misalignment should be taken into account in the design of the mode coupler to allow for a scalable solution. Mode coupling between the GaAs and SiN waveguide will be realized evanescently through a 50 nm bonding layer. To model this component, a stepwise linear taper was designed similar to the method of [9]. It relies on the inspection of the optical modes in the waveguiding system. For this system, one can look into both its coupled (hybrid) and uncoupled (standalone) modes. In Figure 1, we show the varying effective index of modes involved for different widths of the GaAs waveguide as well as the mode overlap of the uncoupled modes with its supermode.

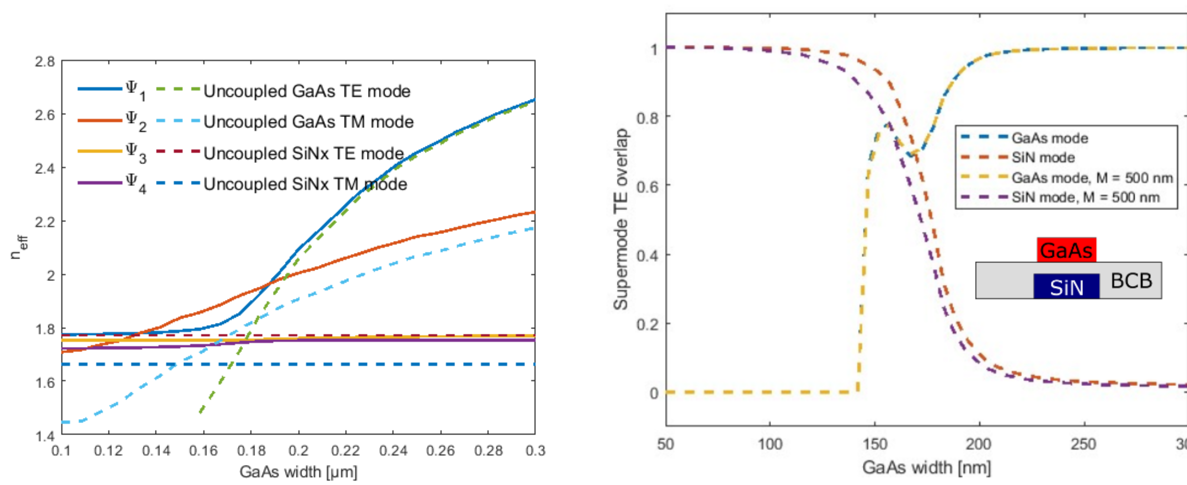

Figure 1: (Left) Effective refractive indices n_{eff} of the different TE/TM-like uncoupled modes and first four supermodes Ψ_i as function of GaAs waveguide width (Right) The overlap between TE-like supermode Ψ_1 and TE-like modes in standalone GaAs and SiN waveguides as a function of GaAs waveguide width for perfectly aligned and 500 nm laterally misaligned mode couplers. Inset: Heterogeneous material layer stack.

It is clear that while still useful, the uncoupled modes fail to overlap perfectly with the hybrid modes. Also a kink in the overlap curve can be observed for the GaAs waveguide mode. Both effects result from the fact that coupled mode theory is a very rough approximation for the case of closely-spaced waveguides with small dimensions with respect to the wavelength and a high refractive index difference. Therefore, most useful is to focus on the coupled modes and the SiN overlap curve. From this, we can deduce that mode coupling occurs when varying the GaAs waveguide width from 100 to 250 nm, crossing a phase-matched region. When also taking into account the fabrication tolerances regarding misalignment and deviations in waveguide widths, we concluded on a design with three tapering sections. The first section spans 5 micron to taper from 80 nm to 115 nm, the second section spans 35 microns tapering from 115 to 215 nm waveguide width and in a final

5 micron length, the waveguide is enlarged to a width of 300 nm. The resulting transmission for different cases of misalignment and waveguide width deviations can be seen in following figure:

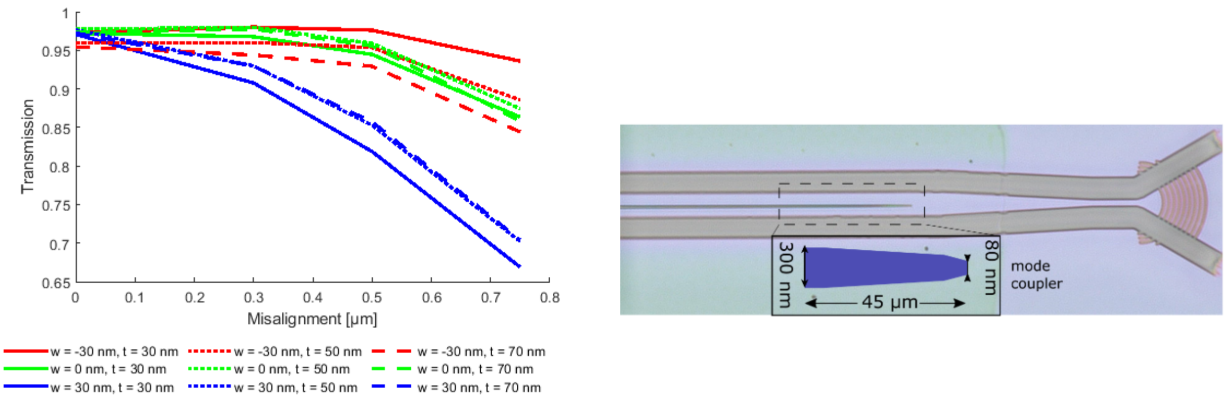

Figure 2: (Left) Mode coupler efficiency as a function of misalignment in case of different bonding layer thicknesses (t) and waveguide width deviations (w) (Right) A microscope image of a fabricated device with a figure of a mode coupler design in the inset

As clear from simulation, $> 90\%$ coupling efficiency over the GaAs-SiN mode coupler is within reach given the above taper design. Even higher coupling efficiency could theoretically be obtained by further elongating the tapering design but at that point the severe propagation losses of 7 dB/ mm in the GaAs material should be considered. In that regard, the above design is a good trade-off with sufficient mode coupling taking into account the simple estimate of the mentioned propagation losses. This can be improved upon in future work by taking into account a model for the propagation losses depending on the waveguide width[10].

4 Fabrication

SiN circuits were fabricated using 300 nm LPCVD nitride which was patterned with electron beam lithography (EBL) and reactive ion etching (RIE). A thin BCB (bisbenzocyclobutene) bonding layer of 50 nm was consequently spin coated on top. In parallel, the GaAs source sample was fabricated. Quantum dots were grown through molecular beam epitaxy (MBE) prior to waveguide patterning. The latter was also performed through EBL and RIE etching. After device patterning, the remaining AlGaAs sacrifical layer was opened through UV contact lithography and inductively coupled plasma (ICP) etching to the GaAs surface. Photoresist tethers and coupon could then be applied through UV lithography, ankering the encapsulated devices to the substrate. With this, devices could be underetched with HCl to realize suspended photoresist coupons entailing the GaAs microphotonic components. At that point, with our micro-transfer printing tool, we could approach the coupons with an elastomer PDMS stamp. Depending on the operating speed applied, adhesion can be strengthened either to the coupon or coupon-to-target. In this way, devices can be automatically picked and placed from their native substrate on top of the target sample aided by the BCB bonding layer which is heated to 70 C. Finally, photoresist encapsulation was removed and the BCB bonding layer was cured at 270 C.

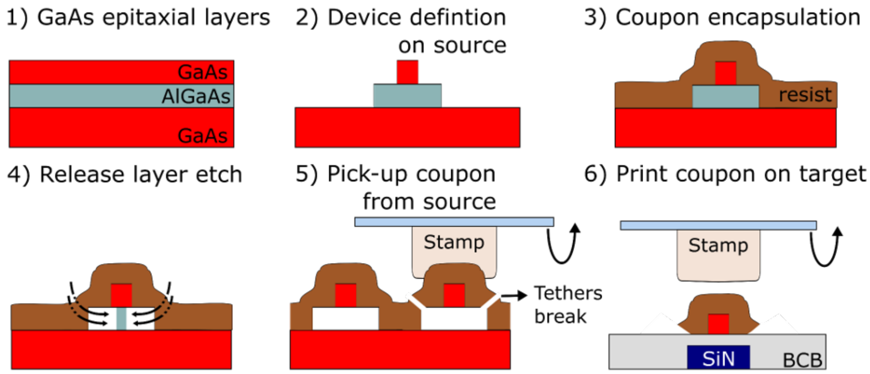

Figure 3: Fabication process of the heterogeneous GaAs-on-SiN structures

The photoresist coupon and fabrication method as shown in the figure above now allows for a lot of design freedom in structures ready for printing. By making the coupon sufficiently large, stress is minimized and complicated devices such as nanobeams and grating couplers but also microdisks, 1D photonic crystals (PhC) and 2D PhC waveguides can now be printed for study in the heterogeneous system.

5 Characterization

Characterization is performed using fiber couplers to adress grating couplers either defined in SiN or printed GaAs. After a thorough characterization, consistent results are obtained across different components. Grating couplers were designed for objective coupling in a cryostat system. For SiN and GaAs couplers, -9.75 dB and -9.5 dB transmission were found even with preliminary fiber coupled setups. For GaAs devices with tapered mode couplers as in Figure 1, 3 dB of excess losses were measured on top of the SiN grating couplers. We estimate around 1 dB of propagation losses for the ∼100 micron long devices. This means mode couplers account for -1 dB of transmission. Further characterization in a 4 K cryostat setup will be the next subject of study as well as single-photon properties after printing. Material stability during cooldown has already been confirmed.

6 Conclusion

A design and fabrication process has been developed to realize a wide range of complicated GaAs-on-SiN structures with an estimated 1 dB coupling loss between both material waveguiding systems. Efficient fiber coupling in the circuit allows for the first experiments with this heterogeneous platform. With these basic building blocks, quantum photonic experiments can now be performed using the GaAs waveguides as single-photon sources at 4 K based on their embedded quantum dots.

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