Overcoming optical losses in a heterogeneous SiN/GaAs platform for quantum photonics

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Abstract

Current proposals for photonic quantum computing based on quantum dots allow for 8 % photon losses to reach fault tolerance[1]. The assumed implementation is based on hybrid approaches where the single-photon source and fusion measurement circuit are realized on separate chips. With fiber coupling of the source chip reported to suffer 50 % photon losses, new avenues have to be explored. In this work, we discuss the heterogeneous integration of quantum dot single-photon sources where optical coupling is currently 82.2 % efficient[2]. We thoroughly cover the allowed losses, their main contributions and possible ways to overcome them in future work.

Introduction: losses in photonic quantum computing with quantum dots

Photonic quantum computing promises room temperature operation and seems resilience to noise given the fact that photons don't easily interact with their environment. Building on CMOS developments, they can be naturally integrated and offer fast gate times. Typical proposals have been based on heralded single photons generated through probabilistic processes such as spontaneous parametric down conversion or four-wave mixing[3]. For the construction of resource states, photons are then entangled again in a probabilistic manner[4]. Consequently, it relies heavily on multiplexing and fiber delays. As a result, it is very challenging to meet the requirements in allowed photon losses without introducing large overheads in photon number per resource state [5].

Alternatively, epitaxial quantum dots might be considered since they can serve as a deterministic entangled photon source[6]. That might dramatically reduce the required overhead and circuit sizes without the need for heralding. Moreover, when multiplexing heralded photon sources in space with extensive switching, *many* photon channels should be taken into account for loss tolerance. This is not the case for recent proposals based on on-demand entangled photon generators[1]. Here, the optical circuit depth for a photon can be fixed to 4 phase shifters and 5-7 beam splitters. The allowed optical losses in that circuit are limited to only 8 % (0.362 dB) to reach the threshold for fault tolerance. In this work, we only discuss the implementation of such a resource state generator. That means we do not include the fusion-measurement circuit chip in our analysis and refer to other ongoing efforts [3] for that technology.

Deterministic resource state generator

In(Ga)As quantum dots embedded in GaAs waveguides are known to be quantum emitters with unmatched quality[7], reaching > 99 % single-photon purity and > 96 % pairwise indistinguishability (coherence). It is essential to reduce decoherence processes in order to obtain such performance. Specifically, the removal of charge noise by embedding the quantum dot inside a p-i-n junction has been indispensable for the demonstration of transform-limited linewidths [8] which is a clear sign of high coherence. Moreover, AlGaAs barrier layers within this heterostructure allow for a single electron to be loaded in the quantum dot, creating charged trion states. With the presence of strong magnetic fields, this allows for Zeeman-splitted energy levels that depend on the spin of the electron [9]. Through optical control pulses, this spin-photon interface allows for the creation of entangled cluster states [6].

The inherent single-photon source efficiency is very high with only 0.223 dB emitted into the broad phonon sideband[7]. In contrast, these on-demand entangled photon sources still fall short in terms of coupling efficiency for their implementation in fusion-based quantum computing. While the threshold for fault tolerance is 8 % as described above, fiber coupling through grating couplers from the source chip is already responsible for photon losses of 50 %[10]. Photon coupling losses to a fusion measurement circuit chip on the other hand is limited to 0.13 dB due to fiber transmission and chip incoupling through fiber arrays.

Heterogeneous integration of deterministic single-photon sources

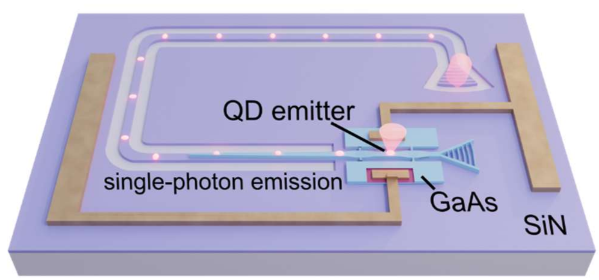

Figure 1: 3D Schematic of the SiN/GaAs platform for quantum photonics

Clearly, direct integration of the entangled photon sources on the fusion measurement chip would be more desirable as this would avoid the many fiber-chip interfaces in current demonstrations. In this work[2], we describe the integration of InGaAs quantum dot emitters embedded in GaAs waveguides onto a SiN target chip through a technique called micro-transfer printing[11]. With a printing yield of 94.7 %, we managed to populate a SiN chip with 36 GaAs devices. As visualized in Fig. 1, this involved nanobeam devices with p-i-n junctions to enable spin control, charge noise suppression and electrical wavelength tuning. Using optimized mode couplers, we achieved a GaAs/SiN coupling efficiency of 82.2 % (-0.85 dB), well-above the fiber coupling efficiencies mentioned in the previous section.

Reducing photon losses

In order to reach the threshold of 0.362 dB for fault tolerant quantum computation, drastic improvements are clearly still needed. Recently, propagating losses as a result of sidewall scattering have been clearly analyzed in the GaAs platform and have been shown to be heavily dependent on the waveguide width for such a thin and narrow nanobeam[12]. Recent improvements have demonstrated that the mode coupler losses can be reduced to 0.4 dB by exploiting this model [13].

Around the same time, highly coherent emission from InAs quantum dots has been demonstrated in the original telecom band for the first time. While emission in this O-band had been demonstrated in the past, it was lacking the required quantum coherence. By embedding the quantum dots in a 7 nm InGaAs quantum well combined with a p-i-n heterostructure, this resulted in transform-limited linewidths as shown before only in the near-infrared. Besides the compatibility with fiber networks, this increase in wavelength also reduces propagation losses from ~20 dB/mm [14] to 3.5 dB/mm. That was expected because of the strong wavelength dependence of the main loss contributions[12]. With propagation losses being a main contributor to our measured GaAs/SiN coupling, we foresee a large reduction in coupling losses by transitioning to the telecom band in future work.

Lastly, while the used SiN grating couplers have not been the main focus of attention, they appeared to be important for the characterization of our single-photon source. While current experiments have focused on optical coupling, single-photon purity and quantum dot blinking, improved overall efficiency will allow for more advanced spectroscopic experiments in future work. That includes resonant transmission[15] to study the light-matter coherence.

Previously reported SiN grating couplers were responsible for 11.5 dB of insertion loss in the characterization of the GaAs/SiN platform. These were regular, fully-etched focused grating couplers. Here, we introduce an improved version that reaches a peak efficiency of -5 dB.

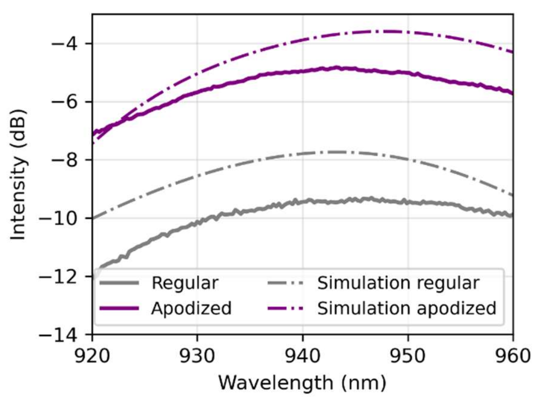

Figure 2: Simulations and measurement results of SiN grating couplers

Similar to mode coupler design, the first step to improve performance was to reach a closer match between simulations and measurements. That involved ellipsometry on the layer stack for improved accuracy of layer refractive index and thickness. Secondly, apodizing of the grating profile for a more Gaussian profile of the light beam played a significant role. The resulting performance from measurements and simulation can be seen in Fig. 2.

To conclude, quantum dot devices can play an important role in photonic quantum computing but this still requires significant improvements in overall photon transmission. Here, we discussed the heterogeneous integration of InGaAs quantum dot single-photon sources to overcome several fiber-chip interfaces. We further commented on improvements in the GaAs/SiN mode coupler as well as the SiN grating coupler for source characterization.

References

[1] ML Chan et al, "Practical blueprint for low-depth photonic quantum computing with quantum dots", *preprint arXiv:2507.16152* (2025)

[2] J. De Witte et al, in preparation (2025)

[3] PsiQuantum team, “A manufacturable platform for photonic quantum computing”, Nature (2025)

[4] S. Bartolucci et al, "Creation of entangled photonic states using linear optics", arXiv preprint arXiv:2106.13825 (2021)

[5] S. Bartolucci et al, "Comparison of schemes for highly loss tolerant photonic fusion based quantum computing", *arXiv preprint arXiv:2506.11975* (2025)

[6] Y. Meng et al, "Deterministic photon source of genuine three-qubit entanglement", Nature communications 15.1 (2024)

[7] R. Uppu et al, "Scalable integrated single-photon source", Science advances 6.50 (2020)

[8] N. Somaschi et al, "Near-optimal single-photon sources in the solid state." Nature Photonics 10.5 (2016)

[9] R. Uppu et al, "Quantum-dot-based deterministic photon–emitter interfaces for scalable photonic quantum technology", Nature nanotechnology 16.12 (2021)

[10] Sparrow Quantum, in preparation (2025)

[11] G. Roelkens et al, "Micro-transfer printing for heterogeneous Si photonic integrated circuits", IEEE Journal of selected topics in quantum electronics, 29.3 (2022)

[12] M. Ljubotina et al, "Origins and Mitigation of Scattering-Related Propagation Losses in Suspended GaAs Waveguides for Quantum Photonic Integrated Circuits", IEEE Journal of Selected Topics in Quantum Electronics (2025)

[13] M. Ljubotina et al, in preparation (2025)

[14] Y, Wang et al, "Electroabsorption in gated GaAs nanophotonic waveguides", Applied Physics Letters 118.13 (2021)

[15] H. Thyrrestrup et al, "Quantum optics with near-lifetime-limited quantum-dot transitions in a nanophotonic waveguide", Nano letters 18.3 (2018)