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Abstract: We report a method for integrating GaAs waveguide circuits containing self-assembled quantum dots on a Si/SiO$_2$ wafer, using die-to-wafer bonding. The large refractive-index contrast between GaAs and SiO$_2$ enables fabricating single-mode waveguides without compromising the photon-emitter coupling. Anti-bunched emission from individual quantum dots is observed, along with a waveguide propagation loss $< 7$ dB/mm, which is comparable with the performance of suspended GaAs circuits. These results enable the integration of quantum emitters with different material platforms, towards the realization of scalable quantum photonic integrated circuits.

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1. Introduction

The development of photonic integrated circuits for quantum applications such as secure communication, sensing, and computing, relies on a robust and scalable chip-scale architecture which can implement all the functionalities for generating and routing light at the single-photon level [1]. Gallium arsenide (GaAs) membranes with integrated self-assembled quantum dots (QDs) grown by molecular beam epitaxy (MBE) offer an excellent platform for single-photon generation and light confinement with near-unity emitter-photon coupling efficiencies and low-noise characteristics [2,3].

A key aspect of GaAs membrane technology is the suppression of out-of-plane photon leakage which enables near-deterministic single-photon generation [4,5]. This results from the high refractive index contrast between GaAs ($n = 3.5$) and air. The MBE-growth of lattice-matched layers, like AlAs, only provides a moderate index contrast to GaAs. Therefore, the realization of a GaAs-based quantum photonic integrated circuit (QPIC) is currently implemented with suspended waveguides [6]. Currently, there is excellent progress in developing suspended waveguide GaAs technology [7], which, however, requires more advanced designs and fabrication methods to avoid collapsing the waveguides on the substrate (e.g. by using thin tethers or supporting ribs [8,9]). Transferring the GaAs membrane on a low-index substrate offers a promising alternative as it would maintain the high photon-emitter coupling efficiency without compromising the device complexity. More importantly, the development of such integration opens up the possibility to combine the high-quality GaAs photon-emitter interfaces with different photonic integrated circuit platforms, such as the Silicon Nitride [10,11] and thin-film Lithium Niobate [12] waveguide technology, both employing SiO$_2$ as cladding material.

Several techniques have been developed to achieve the heterogeneous integration of III/V semiconductor stacks on silicon substrates [13,14] primarily targeting the integration of coherent
light sources with CMOS-compatible fabrication processes. Similarly, single-photon sources (SPS) have been integrated on Si using, e.g. pick-and-place assembly [10,15,16], flip-chip [17], and direct epitaxial growth of GaAs on a Si substrate [18]. Additionally, several works have reported SPS on Si-based platforms fabricated via the micro transfer printing method [19–21] and bonding method through surface forces [22]. Yet, none of these works have demonstrated GaAs waveguide circuits with quantum emitters fabricated on a low-index platform.

In this work, we demonstrate GaAs photonic circuits featuring embedded QDs, fabricated on a thick thermally-oxidized SiO\(_2\) layer \((n_s = 1.45)\) on a Si substrate. The concept is illustrated schematically in Fig. 1(a). We use die-to-wafer bonding with subsequent GaAs substrate removal [23] to transfer a GaAs membrane on Si/SiO\(_2\) wafer and process the whole stack directly. The choice of an adhesive polymer for bonding over other surface bonding techniques (e.g. active surface bonding or oxide bonding) helps achieve uniform adhesion between non-perfectly planar surfaces and provides tolerance to particle contamination, without observable degradation of the waveguide loss and fabrication quality. QD-based SPS emitting in the telecom O-band have been previously realized by such a method [24,25], but not in waveguide circuits. The wafer bonding employed in this work offers a practical and scalable technique which enables the fabrication of GaAs waveguide circuits directly on a low-index substrate without the need of advanced and high-resolution equipment for the precise die-to-die alignment. We characterize the optical transmission losses at room and low temperatures, showing the vacuum-compatibility and cryogenic-compatibility of the fabricated structures.

**Fig. 1.** (a) Schematic view of the integrated photonic structure featuring GaAs waveguides with embedded QD and vertical grating couplers, bonded on a Si/SiO\(_2\) substrate with a polymer layer. (b) Schematic cross-section of the bonded sample. (c) First wet etching process, which thins down the GaAs substrate. (d) Second selective wet etching process. (e) Sacrificial layer removal. (f) Definition of alignment marks. (g) Fabrication of photonic nanostructures.
2. Device fabrication

The III-V wafer is grown by MBE on a 630 µm-thick GaAs substrate. It contains a 1370 nm-thick Al0.75Ga0.25As sacrificial layer and a 160 nm-thick GaAs membrane with a layer of self-assembled QDs in the center. The target wafer is a Si substrate with a thermally-grown 1000 nm-thick SiO2 layer cleaved in ~ 10 × 10 mm2 dies. Figures 1(b)-(g) outline the fabrication steps used in the preparation of the samples. An optically-transparent cryo-compatible polymer (mr-DWL 5, from Microresist GmbH) is used as the intermediate adhesive layer for ensuring uniform bonding between the two surfaces. The adhesive is diluted in a γ-Butyrolactone:mr-DWL (1:3) solution prior to spin-coating on the SiO2 surface, resulting in a 160 nm thick layer. A smaller ~ 8 × 8 mm2 GaAs die is flipped upside down and placed on the coated SiO2 layer, manually aligned to its center (Fig. 1(b)). To strengthen the bonding, the polymer is placed on a hotplate at 60 °C while applying a gentle pressure (~7.5 N cm−2) from top, and baked by gradually increasing the temperature to 140 °C for approximately 45 minutes. The backside of GaAs is chemically etched in two steps [26]. First, a fast and non-selective wet etching process in 1HNO3:4H2O2:1H2O is performed for 115 min, until about 50 µm of GaAs is left (Fig. 1(c)). Then the sample is immersed in a 1NH4OH:19H2O2 solution, which is slower and selective to AlGaAs (Fig. 1(d)). The remaining AlGaAs sacrificial layer acts as an etch-stop layer in the previous etching step. In Fig. 1(e) it is removed in cold hydrochloric acid (2 °C) to avoid damaging the underlying SiO2 layer.

Photonic nanostructures are fabricated on the membrane following the same procedure used for suspended GaAs waveguides, as described in a previous work [6]. Cr/Au (10/170 nm) alignment markers are defined via a sequence of e-beam lithography at 125 keV (Elionix F-125), metal deposition, and lift-off (Fig. 1(f)). Subsequently, GaAs shallow-etched grating couplers are fabricated by electron-beam lithography (EBL) followed by a controlled reactive ion etching (RIE) in a BCl3/Ar plasma, with a desired etch depth of 50 nm. Finally, the 300-nm-wide waveguides are fabricated via EBL and a deep RIE etching through the whole GaAs membrane (Fig. 1(g)). After completing the fabrication of the nanostructures on the hybrid substrate, the sample is further cleaved in smaller chips with 4 × 4 mm2 dimensions, to fit inside a cryostat chamber for low-temperature measurements.

Scanning electron microscope (SEM) images and atomic force microscope (AFM) scans have been taken on various parts of the chip, to inspect the quality of the outcome of the fabrication process. The samples feature several short straight nanobeam waveguides with input and output shallowly-etched focusing grating couplers [27], shown in Fig. 2(a) and a set of concentric waveguides with different lengths, shown in Fig. 2(b), for measuring the propagation loss [28]. The waveguides are designed to support the propagation of a single guided transverse electric (TE) mode. The three-dimensional (3D) AFM topography images of the vertical grating coupler is presented in Fig. 2(c) and a cross-section along the grating axis (marked by the red dashed line) is plotted in Fig. 2(d). The etch depth reduces slightly on one side due to the RIE lag upon the gradual reduction of the grating pitch, which reduces back-reflection and improves the collection spot shape [27]. Figure 2(d) confirms that the shallow-etched gratings, which are one of the smallest features in the mask, meet the desired size and etch depth previously reported for bulk GaAs nanofabrication, indicating that the presence of a different substrate does not visibly influence the lithography and dry etching steps. Moreover from the AFM analysis on different parts of the sample, we have observed that the surface root mean square (rms) roughness is 1.2 nm, which is comparable with previously reported values in GaAs after the removal of AlGaAs etch-stop layers [29].
3. Optical characterization

The samples are characterized in a He-flow cryostat, both at room and at cryogenic (10 K) temperatures. We perform optical transmission measurements using a supercontinuum laser source (SuperK EXTREME). Light is coupled through the grating coupler via a microscope objective and the transmitted light is collected via the same objective and analyzed by a spectrometer. Figure 3(a) shows the transmission spectra (normalized to the peak transmission) for the shortest waveguide (around 100 µm long) at both cryogenic (10 K) and room temperatures (295 K). Both spectra show bell-shaped transmission curves compatible with the grating bandwidth of suspended waveguides [27]. By repeating the transmission measurement on a set of concentric waveguides with different lengths (see Fig. 2(b)), assuming identical response from each grating, the intensity drop is fitted to a linear absorption model, following the procedure outlined in [28], and the propagation loss and respective uncertainties are extracted at different wavelengths.

In Fig. 3(b), the propagation loss per mm is plotted, in logarithmic scale, as a function of wavelength. The error bars represent the standard deviation on the best fit parameters. For comparison, the propagation loss of suspended waveguides at cryogenic temperature (black dots in Fig. 3(b)) is reported. At the transmission peak wavelength of the grating at cryogenic and room temperature, i.e., 933 nm and 956 nm, a loss of \((-11.6 \pm 1.0)\) dB/mm and \((-26.0 \pm 4.3)\) dB/mm are obtained, respectively. The \(-23\) nm shift on the transmission peak matches the shift observed in suspended GaAs grating couplers [27] and is compatible with the shift of refractive index with temperature. At longer wavelengths (>945 nm) the loss drops to \((-6.9 \pm 0.7)\) dB/mm, which is in good agreement with the propagation loss measured on conventional suspended waveguides and previously reported in [9,28]. The loss is strongly wavelength- and temperature-dependent, with the higher loss occurring at shorter wavelengths and higher temperature. Such behavior is typical and in qualitative agreement with Franz-Keldysh electroabsorption, and has been previously observed to occur up to \(\sim 200\) meV inside the GaAs bandgap in the presence of strong electric fields [28]. Electroabsorption is normally not observed in undoped suspended GaAs waveguides,
where the loss is nearly wavelength-independent in the 920–950 nm range. Therefore, we suspect that the polymer and the underlying SiO$_2$ substrate have been charged due to the EBL exposure [30] at 300–600 µC/cm$^2$ and cause a $>100$ kV/cm uniform electric field in proximity of the waveguides.

![Graph](image)

**Fig. 3.** (a) Transmission spectra for the inner concentric waveguide ($L = 99$ nm) at room (295 K, in orange) and cryogenic temperatures (10 K, in blue). The weak interference fringes are caused by back-reflections at the grating couplers. (b) Propagation loss per mm (in dB) at room temperature (in orange), at cryogenic temperature (in blue), and for the previously fabricated suspended waveguides at cryogenic temperature (in black) versus wavelength. The error bars are estimated from the fit procedure.

The QD photoluminescence spectrum is measured in the nanobeam waveguide of Fig. 2(a) by exciting the spot marked in the figure with an above-band pulsed laser at 776 nm, with 40 MHz repetition rate. Figure 4(a) shows a typical spectrum of the QD emission collected from the device. Several emission lines are visible (marked with X$_n$ in the figure), and correspond to multiple excitonic transitions. The emission intensity for the peak X1 as function of the laser excitation power is plotted in Fig. 4(b). This emission line exhibits a typical saturation behavior, from which we extract the saturation power by fitting the data with $I = I_{\text{max}} (1 - \exp(-P/P_{\text{sat}}))$ (solid orange line in Fig. 4(b)), where $P$ is the pump laser power at the sample, $P_{\text{sat}}$ is the exciton saturation power, $I$ is the number of counts and $I_{\text{max}}$ is the maximum counts. Accordingly, a saturation power of $P_{\text{sat}} = 0.18$ µW is extracted at $I = 0.63\cdot I_{\text{max}}$. The maximum number of total counts observed is $\sim 10$ kHz.

To characterize the single-photon nature of the QD emission, Hanbury-Brown and Twiss (HBT) correlation measurements have been carried out. For this purpose, the X1 emission line, i.e., 937.86 nm, has been filtered using a grating filter with bandwidth $\sim 0.2$ nm, and a 50:50 fiber beam-splitter and two avalanche photo-diodes (APDs) have been added to the measurement setup, schematically depicted in Fig. 4(c). We have characterized the photon propagation efficiency from the sample to the APDs and estimated the photon counting rate before the objective lens of the photon collection path to be $\sim 1.8$ MHz. A time-tagging module records correlation events between the two detectors. Figure 4(d) shows an auto-correlation function $G^2(\tau)$, where the coincidence rate has been plotted as a function of the coincidence time delay between the two APDs at $P = 1.3 P_{\text{sat}}$ (the power specified by the circle in Fig. 4(b)). An anti-bunching dip is observed at zero time delay, confirming the single-photon nature of the emission line from the QD. The above-band excitation allows for photon emission via multiple pathways and weakly excites other neighbouring defects, giving rise to broad features in the emission spectra. A substantial amount of the counts, highlighted by the dashed red line in Fig. 4(d), does not allow us to observe the peak at zero time delay and to extract the exact value of $G^2(0)$, but only to identify an upper bound to approximately 40%, that confirms the single-photon nature of the emitted light. To reach a more precise estimate, a sample with lower QD density, together with a narrower filtering apparatus will be needed, potentially adopting p-shell or quasi-resonant excitation techniques.
to further clean the spectrum from unwanted emission. Moreover, developing gated samples with QD embedded in $p$-$i$-$n$ structures is expected to further enhance the quality of the emitted photons [31].

4. Conclusion

We demonstrated the heterogeneous integration of GaAs waveguides with quantum dots on a silica substrate. The AFM and SEM scans and optical measurements show that the fabrication method presented here enables developing GaAs-based waveguide circuits with single-photon emitters without degradation of performance, compared to traditional suspended waveguides. To further reduce the waveguide loss, the charging effects from the adhesive polymer should be reduced, for example by coating the e-beam resist with thin Au layers before EBL exposure [32]. Furthermore, to gain control over the charge noise processes in QDs, future work will investigate the fabrication of electrically-gated $p$-$i$-$n$ junctions, required for coherent and indistinguishable single-photon emission [31]. The integration of GaAs waveguides with embedded QDs on a SiO$_2$ layer is an important step forward towards the heterogeneous integration of GaAs-based devices with different material systems [33,34], such as low-loss SiN waveguides [35–37] and lithium niobate thin films [38,39], towards a fully scalable and hybrid QPIC technology.

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References


