Monolithic on-chip integration of semiconductor waveguides, beamsplitters and single-photon sources

Klaus D Jöns\textsuperscript{1,2,3}, Ulrich Rengstl\textsuperscript{1,2}, Markus Oster\textsuperscript{1}, Fabian Hargart\textsuperscript{1}, Matthias Heldmaier\textsuperscript{1}, Samir Bounouar\textsuperscript{1}, Sven M Ulrich\textsuperscript{1}, Michael Jetter\textsuperscript{1} and Peter Michler\textsuperscript{1}

\textsuperscript{1} Institut für Halbleiteroptik und Funktionelle Grenzflächen and Research Center SCoPE, University of Stuttgart, Allmandring 3, 70569 Stuttgart, Germany

E-mail: u.rengstl@ihfg.uni-stuttgart.de

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Abstract

The implementation of fully integrated single-photon sources and detectors into waveguide structures such as photonic crystals or a slab and ridge waveguide is currently one of the major goals in the linear optics quantum computation and communication community. Here, we present an implementation of a single-photon on-chip experiment based on a III–V semiconductor platform. Individual semiconductor quantum dots were used as pulsed single-photon sources integrated in ridge waveguides, and the on-chip waveguide-beam splitter operation is verified on the single-photon level by performing off-chip photon cross-correlation measurements between the two output ports of the beamsplitter. A degree of polarization of the emitted photons above 90\% is observed and a careful characterization of the waveguide propagation losses in straight (\(<1.5\) dB mm\(^{-1}\)) and bent (\((8.5\pm2.2)\) dB mm\(^{-1}\)) sections documents the applicability of such GaAs-based waveguide structures in more complex photonic integrated circuits. The presented work marks an important step towards the realization of fully integrated photonic quantum circuits including on-demand single-photon emitters.

Keywords: quantum dots, single photons, waveguides, photonic integrated circuits, integrated beamsplitter

(Some figures may appear in colour only in the online journal)

1. Introduction

Shortly after the pioneering work of Knill, Laflamme and Milburn which opened the field of linear optics quantum computation [1], first optical two-photon gates have been realized [2, 3]. These experimental demonstrations of such an optical controlled-NOT gate have been made with bulky optics. However, the applicability of quantum information science [4] relies strongly on the on-chip integration, i.e. miniaturization, of such devices. In 2008, the first on-chip quantum logic gate was reported by Politi \textit{et al} [5] and several important applications followed [6–9], showing the power of integrated photonic quantum circuits. However, all these previous studies have been realized by use of external photon sources based on probabilistic parametric down conversion [5]. On the basis of silicon substrates, an integration of on-demand single-photon sources, such as single quantum emitters, is exceptionally rare [10, 11], whereas waveguide integration has not been reported to the best of our knowledge. One approach to integrate the photon source on-chip is integrated waveguide four-wave mixing [12, 13]. However, these sources rely on an interaction length, which is very large in terms of desirable on-chip scales and they deliver Poissonian photon statistics. Nonlinearities
can also be used with III–V semiconductor-based photon sources, for example by integrated spontaneous parametric down-conversion in GaAs/AlGaAs Bragg-reflection waveguides [14].

On the other hand, III–V semiconductors are also perfectly suitable for the integration of quantum dots (QDs) as triggered single-photon [15] and entangled photon pair sources [16, 17]. Single QDs in photonic crystal (PC) cavities have also been used as controlled-NOT gates operating on externally generated photons [18]. Using GaAs as the platform, very efficient waveguiding in PC structures has been realized [19]. Additionally, the coupling of single QDs to the propagation mode of the PC waveguide enhances their spontaneous emission rate [20]. Indeed, very efficient guiding of their single-photon emission has been reported [21], even for the conditions of only weak Purcell enhancement [22]. It has been shown that the coupling of single QDs to the waveguide mode can be enhanced by designing the PC waveguide to act as a Fabry–Pérot cavity [22] or by coupling QDs to PC nanocavities [23].

Ridge and rib-type photonic channels have also been studied on this material system, and low-loss waveguiding was reported [24]. Even a spin-photon interface was realized by coupling QDs to two orthogonal waveguides [25]. Additionally, it has been shown that ridge waveguides are suited for integrating superconducting single-photon detectors [26]. Using such detectors, on-chip time-resolved photon counting from an ensemble of integrated QDs has been recently reported [27]. One major prerequisite for the realization of quantum photonic integrated circuits based on QDs is the on-chip generation of single photons from individual QDs together with the functionality of beamsplitter operations on the single-photon level. This was very recently demonstrated on an air clad, free standing directional coupler [28]. In this letter, we present such a single-photon functionality of an on-chip 50/50 beamsplitter using the coupling between two distributed Bragg-reflection ridge waveguides with monolithically embedded InGaAs/GaAs QDs as single-photon sources. In addition, a detailed analysis of the optical losses in straight and bent waveguides, together with a polarization analysis of the guided photons, is performed.

2. Design of the waveguide structure

The layer structure of the presented device was grown by metal-organic vapor-phase epitaxy (MOVPE) using a (1 0 0)-GaAs substrate, with a miscut of 6° to the (1 1 1)A facet. This miscut is a prerequisite for the growth of the used QDs [29]. Figure 1(a) shows a scanning electron microscope (SEM) image of the cross-section of the finalized structure, where the grown layer sequence (see schematic drawing in figure 1(b)) is clearly visible. It consists of 20 pairs of distributed Bragg-reflectors (DBR) at the bottom, which are obtained by the alternating deposition of AlAs and GaAs layers. On top of this DBR structure the waveguide core is deposited, consisting of a 267 nm thick GaAs layer. The use of the III–V semiconductor material enables the implementation of InGaAs/GaAs QDs as single-photon emitters using the self-organizing Stranski–Krastanow growth mode. To enhance the coupling efficiency between QDs and the waveguide, they were grown in the center of the GaAs core layer. The vertical confinement is finished by an additional set of 4 pairs of DBRs at the top. The DBR structure was optimized for vertical detection of the QD emission around 930 nm, which allowed detailed characterization [29, 30].

A sketch of the used waveguide structure is shown in figure 1(c). In contrast to [5], we are using multi-mode waveguides with a width of 2 µm and a directional multimode coupler without a gap between the waveguides. The waveguides were orientated towards the (0 1 1) direction to enhance the coupling of photons from dipoles aligned along the (0 1 1) direction. The splitter design was optimized using a commercial beam propagation software (RSof Photonics Suite). The coupler has a nominal length of 118.5 µm, which should lead to a 50/50 splitting ratio at 910 nm. This coupler is surrounded by cosine shaped bends to separate the two beams to a distance of 50 µm within 437.1 µm. Based on the simulations the length of the bends was optimized to create a near unity transmission for the fundamental mode without any mode conversion. Due to the dependency of the splitting ratio on the coupler length, the merging regions of the waveguides have to be created with high accuracy. Therefore, the structure was written using electron beam lithography with a negative tone resist based on hydrogen silesquioxane (HSQ), which forms a highly resistive SiO2 mask after developing. The subsequent structuring by an inductively coupled plasma reactive ion etching (ICP-RIE) ICP-100 system (Oxford Instruments) was carried out using chlorine-based chemistry. This step was monitored via an in situ laser interferometer which allowed the precise stop of etching in the GaAs layer of the 5th mirror pair of the bottom DBR. A cleaved facet of the etched waveguide is shown in figure 1(a). The obtained sidewalls have an angle of less than 7° to the vertical, which is introduced by mask erosion during the etching process.

3. Optical characterization and comparison with theory

For the optical characterization, the sample was cleaved perpendicular to the waveguides, as shown in figure 1(a), leaving a 200 µm long straight section before the first bent section. The sample was placed on a motorized stage inside a He-flow cryostat and cooled to 5 K. The excitation was carried out from the top with a fiber coupled titanium-sapphire laser through a microscope objective with a NA of 0.45. The minimal spot diameter of the excitation beam was approximately 2 µm on top of the sample. The fiber coupler and microscope objective were placed on a motorized stage to allow independent optimization of laser excitation and detection. The emission from the waveguides was measured at an angle of 90° through a fixed microscope objective with a NA of 0.45. For cross-correlation measurements, we split the collected photons from
the individual waveguide output ports after the objective and mapped them simultaneously to two different spectrometers attached with single-photon detectors (figure 1(d)).

To estimate the structural quality of the etched structure, the optical losses of the waveguide were determined. Using a continuous wave laser at 807 nm, above the GaAs barrier, the QDs were excited to the saturation level. The beam spot was scanned along the waveguide and we measured the QD emission through the cleaved edge of the waveguide arm ‘a’, as shown in figure 2(a). These measurements were performed in three different configurations, i.e. excitation on the detection arm ‘a’ (blue) in front of the beamsplitter, within the coupling region itself (green) as well as on both arms ‘c’ and ‘d’ behind the coupler (blue and red colored lines in figure 2(a)). Figure 2(b) shows the corresponding attenuation of the measured maximal intensities plotted as a function of the straight distance to the cleaved facet. We measured 70 QDs in the waveguide splitter and, for comparison, 56 QDs in a straight waveguide from the same sample. The propagation losses of both structures are determined by analyzing the attenuation of the measured intensities over their distances to the cleaved facet. This is done by an exponential fit to the maximum peak intensities over their distances to the facet. This is done by an exponential fit to the maximum peak intensities over their distances to the facet. The obtained loss is with (8.5 ± 2.2) dB mm⁻¹ slightly higher than the value obtained above, but still within the error margins, confirming the above obtained losses. With these values, it can be estimated that each bend introduces in total (3.1 ± 0.9)–(3.7 ± 0.9) dB of loss.

For comparison, we did the same measurements with two straight waveguides, leading to losses between 0.8 dB mm⁻¹ and 1.5 dB mm⁻¹. This is a clear hint that most of the losses originate from the waveguide bends. The obtained losses are in good agreement with recently obtained values on GaAs-based ridge waveguide structures [27]. The losses inside and behind the coupler could not be determined, due to the wavelength- and mode-dependent splitting ratio, which is discussed below. This wavelength- and mode-dependent splitting ratio also inhibits a clear observation of a 50% reduction of the measured intensity inside and behind the coupler region, which would be expected for a perfect 50/50 beamsplitter.

In the following, we have estimated the on-chip efficiency of the device and used it to predict an overall efficiency for the whole setup. We define the overall efficiency as the probability to detect one photon of a certain QD through one detection arm (‘c’ or ‘d’) per excitation pulse of the pump.

![Figure 1. Sample design and optical setup. (a) SEM image of the cleaved facet of a Bragg-reflection waveguide structure with 4 DBR pairs on top and 20 DBR pairs at the bottom of the waveguide core. (b) Schematical layer structure. (c) Visualization of the integrated 50/50 beamsplitter with a directional, multi-mode coupler in the middle, surrounded by cosine-shaped bends. The embedded QDs are excited in only one arm, whereas the emission is detected from both arms. (d) Diagram of the optical setup. Both output ports of the waveguide structure can be mapped to different spectrometers.](image-url)
laser. However, the on-chip efficiency is the probability that a photon from this QD reaches the end of one detection arm ('c' or 'd') before coupling into free space. One major factor which limits the on-chip efficiency is the coupling of the quantum dot luminescence into the waveguide. This efficiency has been estimated by two-dimensional (2D) (range: 100 μm) and three-dimensional (3D) (range: 40 μm) finite-differential time-domain (FDTD) simulations using the free software package Meep [31]. We obtain a theoretical coupling efficiency of a perfectly centered and aligned dipole into the waveguide core of $\beta = (7 \pm 1)\%$. For QDs with a distance of 915 μm to the cleaved facet, like the one used for the cross-correlation measurement below, we obtain an additional attenuation of $(66 \pm 12)\%$ from figure 2(b). If we assume an ideal quantum efficiency of our QDs ($\eta = 100\%$), this would lead to an on-chip efficiency of $(2.4 \pm 1.2)\%$ at the output ports ('a' and 'b') before emission into free space. However, for the overall efficiency we have to take into account the coupling efficiency from the output port ('a' or 'b') into free space. This efficiency is again estimated by 2D FDTD simulations and determined to be less than $(6.8 \pm 1.0)\%$. These high losses are supposed to originate mainly from the internal reflection of higher modes with low propagation constants [32]. This multimode behavior can be observed in 2D simulations of the horizontal cross-section of the waveguide. By additionally taking into account the collection efficiency of our objective of 33% and the total measured efficiency of our optical setup of $(6.0 \pm 0.5)\%$ for detection around 910 nm, including the avalanche photo diodes (APDs), we can derive a theoretical overall efficiency of $(0.0032 \pm 0.0023)\%$. This efficiency might be reduced due to additional scattering effects on the cleaved facet and a possible internal quantum efficiency of the QDs below one [33, 34], but is already in good agreement with the measured efficiencies as shown below.

Figure 3 depicts quantum dot spectra collected from the end facets of the detection arms ('a' and 'b') while exciting in arm 'c' of the beamsplitter. Figure 3(a) shows spectra collected simultaneously with two different spectrometers like in the setup explained in figure 1(d). This setup configuration was used to perform cross-correlation measurements of the two output arms of the waveguide. However, since two different spectrometers were used we cannot extract the beamsplitter ratio from these measurements. Instead, the splitting ratio of the waveguide beamsplitter has been determined by measuring the signal from both detection arms ('a' and 'b') using the same detection path and detector alternately on both arms 'a' and 'b'. The detection signal was optimized on the same QD for both measurements while keeping the excitation power constant. The excitation laser was set to pulsed operation with 2 ps-pulses and tuned to the wetting layer at 864 nm. Figure 3(b) shows two QD spectra taken at the two different output ports ('a' and 'b'). Three emission lines with comparable intensities can be identified. Their splitting ratios are between 0.40 and 0.45, whereas the QDs in the high-energetic tail of the broad QD ensemble between 900 nm and 915 nm show a wide variation of splitting ratios between 0.45 and 0.90, which suggests a splitting ratio close to 0.5 for the wavelength region around 894 nm. This corresponds to an effective length of the coupler of $(122 \pm 2)\mu$m, which is in good agreement with the designed coupler length of 118.5 μm and with the SEM-measurements showing a value of $(121.3\pm 1)\mu$m. The wide spread of the splitting ratios of QDs emitting at a higher wavelength than 894 nm shows the wavelength dependent splitting ratio of directional couplers. This is further enhanced by the multimode behavior of the waveguides and leads to an expected splitting ratio at 915 nm between 0.52 (0th order) and 0.91 (4th order) for different propagation modes. This also causes higher spreading of the measured intensities for QDs behind the coupler as observed in figure 2(b). It also leads to a reduction of the measured intensity for the transmission path (arm 'd' to 'a') of 35% on average in respect to the reflection path (arm 'c' to 'a').

Figure 2. Determination of the propagation losses. (a) SEM picture of a measured waveguide coupler. For better visualization, the image is stretched in the vertical direction. (b) Attenuation of the QD emission in dependence on the distance between the QD and the cleaved facet of the detection arm ‘a’. The corresponding beam spot position is marked in the SEM picture (a) (blue squares: QD-excitation on arm ‘a’ and ‘c’, red diamonds: excitation on arm ‘d’, green squares: excitation in the coupler region). The black circles correspond to a straight waveguide. The shown lines depict the exponential fits to the data for a straight waveguide and the bent section of a beamsplitter with attenuations of 1.0 dB mm$^{-1}$ and 7.2 dB mm$^{-1}$, respectively.
polarization (DOP) when detecting from the side. In fact six of the nine QDs show a DOP above 90%, and eight of the nine a DOP >75%, with the main polarization axis oriented in the horizontal plane (figure 4(a)). This corresponds to the expected behavior assuming a heavy-hole exciton dipole moment oriented along the (011) direction, perpendicular to the waveguide [35, 36]. The non-unity DOP, found over the whole waveguide, can be explained by three possible mechanisms. One possibility is the ground state mixing between light holes and the predominant heavy holes. This mixing could be a result of the partly oxidized, strained AlAs layers of the DBR structures. A contribution of light-hole excitons in the emission would lead to an additional bright state with the dipole moment along the growth direction [35–37]. Another mechanism would be the spurious coupling of a QD dipole moment oriented parallel to the waveguide (011) direction, perpendicular to the waveguide [35, 36]. The non-unity DOP, found over the whole waveguide, can be explained by three possible mechanisms. One possibility is the ground state mixing between light holes and the predominant heavy holes. This mixing could be a result of the partly oxidized, strained AlAs layers of the DBR structures. A contribution of light-hole excitons in the emission would lead to an additional bright state with the dipole moment along the growth direction [35–37]. Another mechanism would be the spurious coupling of a QD dipole moment oriented parallel to the waveguide (011) direction, perpendicular to the waveguide [35, 36]. The non-unity DOP, found over the whole waveguide, can be explained by three possible mechanisms. One possibility is the ground state mixing between light holes and the predominant heavy holes. This mixing could be a result of the partly oxidized, strained AlAs layers of the DBR structures. A contribution of light-hole excitons in the emission would lead to an additional bright state with the dipole moment along the growth direction [35–37]. Another mechanism would be the spurious coupling of a QD dipole moment oriented parallel to the waveguide (011) direction, perpendicular to the waveguide [35, 36]. The non-unity DOP, found over the whole waveguide, can be explained by three possible mechanisms. One possibility is the ground state mixing between light holes and the predominant heavy holes. This mixing could be a result of the partly oxidized, strained AlAs layers of the DBR structures. A contribution of light-hole excitons in the emission would lead to an additional bright state with the dipole moment along the growth direction [35–37]. Another mechanism would be the spurious coupling of a QD dipole moment oriented parallel to the waveguide (011) direction, perpendicular to the waveguide [35, 36]. The non-unity DOP, found over the whole waveguide, can be explained by three possible mechanisms. One possibility is the ground state mixing between light holes and the predominant heavy holes. This mixing could be a result of the partly oxidized, strained AlAs layers of the DBR structures. A contribution of light-hole excitons in the emission would lead to an additional bright state with the dipole moment along the growth direction [35–37]. Another mechanism would be the spurious coupling of a QD dipole moment oriented parallel to the waveguide (011) direction, perpendicular to the waveguide [35, 36].

To verify the beamsplitter operation of our device on the single-photon level, we also performed cross-correlation measurements between the two output ports (‘a’ and ‘b’) of the waveguide during pulsed excitation of a QD behind the coupler (arm ‘c’). The measurement shows a clear antibunching behavior. A multiplex fit (red line) with fixed background correction reveals a $g^{(2)}(0)$ value of 0.42 ± 0.06.
APDs and was calculated using the count rates and dark count rates of both APDs. This yields a $g^{(2)}(0)$ value of 0.42 ± 0.06. The $g^{(2)}(0) < 0.5$ boundary is a sufficient condition to verify that most of the coincidences in our measurement originate from single-photons impinging on the beamsplitter, thus demonstrating the functionality of our on-chip beamsplitter at the single-photon level.

4. Conclusion

In summary, we have demonstrated a monolithically fabricated beamsplitter operating on single photons generated by QDs as integrated on-chip single-photon emitters. Our results show that the used GaAs material system is highly suitable as an integration platform, showing propagation losses below 1.5 dB mm$^{-1}$ for straight sections and bending losses between (7.2 ± 2.0) dB mm$^{-1}$ and (8.5 ± 2.2) dB mm$^{-1}$. The increase of the propagation losses in the bent section by a factor of 6 is not predicted in the beam propagation simulations and may result from interactions with rough sidewalls. A redesign with sharper but shorter bends in combination with straight sections may therefore allow for the reduction of bending losses.

The overall efficiency of the device is in good agreement with the expected values obtained by FDTD simulations. However, the usefulness of fully integrated quantum photonic circuits in quantum networks depends on the on-chip efficiency, since the signal will be detected on-chip without the necessity of coupling to external objectives. Our device exhibits an estimated on-chip efficiency of approximately (2.4 ± 1.2)% . This is currently mainly limited by the theoretical coupling efficiency of $\beta = (7 ± 1)%$ for a perfectly aligned QD into the ridge waveguide modes and can be enhanced in the future by the integration of photonic crystal waveguides, where coupling efficiencies of 89% have been demonstrated [20]. Such structures suffer from higher propagation losses due to multiple scattering at fabrication imperfections. However, as recently outlined by Lohdal et al [41], one solution might be a hybrid structure where the photonic crystal, in which the QDs are embedded, is coupled to ridge waveguides, where the emitted photons can propagate over longer distances. Another solution would be the usage of free standing waveguides, which was reported in [28] during the publication process of this paper. Furthermore, the usage of integrated detectors will allow a shrinking of the needed separation of the detection arms from the optical separable 50 µm to only a few micrometers, which will lead to a significant reduction in the length of the waveguide structure. Supposing the losses of the coupling region to be at most as high as the losses of the waveguide bends (see figure 2), the loss in the whole coupling region with a length of 118.5 µm can be estimated to about 1 dB. This allows the integration of several beamsplitters on one single chip in the future. To enhance the robustness of the splitting ratio, a shrinking of the waveguide dimensions will be feasible in the future to obtain single-mode operation, which would also enable a step forward from a 50/50 beamsplitter to a Hadamard gate operating on indistinguishable photons.

The fabricated device itself shows this desired splitting ratio near 0.5 at a wavelength region around 894 nm. Furthermore, the operation on a single-photon level has been verified by cross-correlation measurements between the two output arms of the device, revealing a $g^{(2)}(0) < 0.5$. The presented combination of the gate operation and the single-photon generation on one single III–V semiconductor chip demonstrates the applicability of waveguide integrated QDs for future quantum photonic integrated circuits.

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Author contributions

KDJ designed and UR fabricated the device. KDJ, UR, MO and SB performed the optical measurements. KDJ, FH, MH and SMU built the optical setup. UR and KDJ prepared the manuscript. SB, SMU, MJ and PM also contributed to the manuscript and supervised all the work.

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