Deterministically fabricated strain-tunable quantum dot single-photon sources emitting in the telecom O-band

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Abstract

Most quantum communication schemes aim at the long-distance transmission of quantum information. In the quantum repeater concept, the transmission line is subdivided into shorter links interconnected by entanglement distribution via Bell-state measurements to overcome inherent channel losses. This concept requires on-demand single-photon sources with a high degree of multi-photon suppression and high indistinguishability within each repeater node. For a successful operation of the repeater spectral matching of remote quantum light sources is essential. We present a spectrally tunable single-photon source emitting in the telecom O-band with the potential to function as a building block of a quantum communication network based on optical fibers. A thin membrane of GaAs embedding InGaAs quantum dots (QDs) is attached onto a piezoelectric actuator via gold thermocompression bonding. Here the thin gold layer acts simultaneously as an electrical contact, strain transmission medium and broadband backside mirror for the QD-micromesa. The nanofabrication of the QD-micromesa is based on in-situ electron-beam lithography, which makes it possible to integrate pre-selected single QDs deterministically into the center of monolithic micromesa structures. The QD pre-selection is based on distinct single-QD properties, signal intensity and emission energy. In combination with strain-induced fine tuning this offers a robust method to achieve spectral resonance in the emission of remote QDs. We show that the spectral tuning has no detectable influence on the multi-photon suppression with $g^{(2)}(0)$ as low as 2-4\% and that the emission can be stabilized to an accuracy of 4 µeV using a closed-loop optical feedback.
The emission of single photons with controllable wavelength and high indistinguishability is a key parameter in quantum light sources for quantum nanophotonics. It is, for example, required to implement boson sampling experiments\(^1\) and to realize entanglement swapping via Bell-state measurements in large-distance quantum communication networks based on the quantum repeater concept.\(^2\)–\(^4\) In fact, in case of the quantum repeater it is crucial to fabricate a chain of wavelength-tunable quantum light sources that provide identical photons on demand. Even more, it is important to operate such light sources at telecommunication wavelengths, i.e. within the telecom O-band (~1.3 μm) or C-band (~1.55 μm), to pave the way towards the real-world implementation of long-distance quantum communication networks based on the quantum repeater concept.\(^2\)–\(^4\)

In this work, we demonstrate technological advances and experimental findings to realize wavelength-tunable quantum emitters of high single-photon purity in the telecom O-band. The strain-tunable emitters are based on self-assembled InGaAs quantum dots (QDs) that are deterministically integrated into photonic nanostructures attached to piezo-elements by means of a flip-chip process.\(^6\) Here, the emission range of the InGaAs QDs is redshifted to the telecom O-band by using a strain-reducing layer (SRL),\(^7\) while the piezoelectric actuator allows us to apply an external strain field to fine-tune and stabilize the QD emission wavelength during operation of the quantum light sources. To demonstrate their application potential, we examined the optical properties of two O-band single-QD mesa structures. The emission of their charged excitonic (CX) states, which are relevant for efficient single-photon generation,\(^8\) are first studied regarding multi-photon suppression. Secondly, we test the wavelength tuning capabilities via strain-tuning and we introduce active spectral stabilization based on a closed-loop proportional-integral-derivative (PID) controller. Finally, we demonstrate strain-tuning and active stabilization of two remote QDs, which can pave the way towards two-photon interference (TPI) of remote sources at the telecom O-band required for the implementation of fiber-based quantum repeater networks.\(^4\)

We manufactured our device in three main technological steps: i) growing a semiconductor heterostructure by metal organic chemical vapor deposition, ii) gold bonding a few-hundreds nm-thin membrane of this structure onto a piezoelectric actuator, and iii) nanostructuring the QD-membrane deterministically by low-temperature cathodoluminescence (CL) scanning and in-situ EBL.

First, a 200 nm GaAs buffer is grown on n-doped GaAs (100) substrate followed by 1 μm thick Al\(_{0.90}\)Ga\(_{0.10}\)As etch stop layer, a 2 μm thick GaAs layer and another 100 nm thick Al\(_{0.90}\)Ga\(_{0.10}\)As layer. These three layers and the substrate are sacrificial layers to be removed.
during post-growth processing. The final 879 nm thick layer of GaAs forms the active device membrane and includes a single InGaAs QD layer combined with the SRL, with the QD layer located 637 nm above the second etch stop layer (see Fig. 1a). The QD layer is formed by 1.5 monolayers of In$_{0.7}$Ga$_{0.3}$As followed by a 0.5 monolayer GaAs flush. The subsequent 5.5 nm thick InGaAs SRL has a gradual decrease of the In-content from 30% to 10% over the first 3.5 nm.

Next, the as-grown sample and a PIN-PMN-PT (Pb(In$_{1/2}$Nb$_{1/2}$)O$_3$-Pb(Mg$_{1/3}$Nb$_{2/3}$)O$_3$-PbTiO$_3$) piezoelectric crystal are sputtered with 250 nm of gold. Their surfaces are then activated under argon plasma and, immediately after being removed from the deposition tool, bonded face-to-face under ambient air and thermocompression. In this step, a pressure of 6 MPa and a temperature of about 600 K are applied. This process allows for a stable bond that is not affected by the inherent surface roughness of the PIN-PMN-PT crystal. For more details on this process, see Ref. 9.

The flip-chip process is finalized by a layer-by-layer wet-etching process. First, the 300 µm thick GaAs substrate is removed by a fast and aggressive etchant (H$_2$O$_2$/NH$_3$, 10:1), stopped at the first Al$_{0.97}$Ga$_{0.03}$As layer due to the high selectivity of the wet-chemical etching process. HCL acid is then used to solely remove the exposed etch stop layer. The now exposed second and thinner GaAs layer (2 µm) is lifted off by a slower etchant (citric acid/H$_2$O$_2$, 4:1), which leads to a significantly improved surface roughness if compared to a single-step etch process. Again, the second etch stop layer is removed by HCL acid. At this point an 885 nm thick membrane, containing the single QD layer, is gold bonded to a PIN-PMN-PT crystal and completely freed from sacrificial layers.

In preparation for the following main processing step the sample is spin coated with a nominal 300 nm thick layer of AR-P 6200 (CSAR 62) electron-beam resist. The sample is then installed in a special scanning electron microscope (SEM) that enables CL measurements at cryogenic temperatures. The sample is cooled to 15 K, and the CL signal is mapped over a 20 x 20 µm large area with 0.5 µm resolution to identify the position of bright and isolated QDs that emit at the desired wavelength in the telecom O-band. A corresponding map showing spatially resolved CL in a spectral range of (1305-1310) nm is shown in Fig. 2a). By applying a 2D Gaussian fit, we can select the two circled QDs in Fig. 2a) with a lateral accuracy of about 40 nm. In the following electron beam lithography (EBL) step, deterministic circular mesa structures are written into the resist at low temperature (10 K) in the same SEM system. When the resist is developed, the image areas are cleared and only the EBL-structured mesa structures remain and form an etching mask for the final reactive ion etching in an inductively coupled
plasma. For the circular QD micromesas with a gold mirror on the back, we expect a moderately high photon extraction efficiency $\eta$ in a range of 5-10\%.\textsuperscript{9,10} This parameter can possibly be increased in the future by applying the present manufacturing method to sources based on circular Bragg resonators that promise broadband photon extraction efficiency up to $\eta = 95\%$ in the telecom O-band.\textsuperscript{11}

Noteworthy, and in contrast to previous work on piezoelectric tuning of QD-micromesas emitting in the 930 nm range,\textsuperscript{12} the etching depth used in the present work corresponds to the thickness of the gold-bonded membrane in our design. Thus, the base diameter of the mesa structure is the only cross section to transfer the strain-field effect at the piezoelectric actuator to the QD position.

The properties of the optical device are investigated by means of microphotoluminescence ($\mu$PL), $\mu$PL-excitation ($\mu$PLE) and photon-correlation spectroscopy at 10 K. The used helium-flow cryostat has an extra high-voltage feed-through to electrically connect the piezoelectric actuator to a voltage supply and a customized spring holder to facilitate strain-tuning of the QD-microlenses. The deterministic QD mesa structures are optically excited by a continuous-wave (cw) diode laser (785 nm) or a tunable pulsed laser providing ps-pulses at a repetition rate of 80 MHz. The photoluminescence signal is collected with an objective (numerical aperture (NA) = 0.4) and spectrally resolved in a grating spectrometer (spectral resolution ~20 µeV). The photon stream can either be detected by a liquid nitrogen cooled InGaAs-array detector or fiber-based Hanbury Brown and Twiss (HBT) and Hong-Ou-Mandel (HOM) configurations attached to the output slit of the spectrometer. The quantum optical configurations include two superconducting nanowire single-photon detectors (SNSPDs) (temporal resolution approx. 50 ps, detection efficiency approx. 80% at 1310 nm).

The device characterization starts by basic $\mu$PL measurements under non-resonant cw excitation (785 nm) at 10 K. We identified two photonic structures with bright CX emission lines at 1303.98 nm (QD1) and 1303.78 nm (QD2). The spectral fingerprints of these two QDs, as shown in Fig. 2b), have three characteristic and representative emission lines, which are identified as neutral exciton (X), singly charged exciton (CX) and biexciton (XX) by excitation-power and polarization dependent measurements (see supplementary information (SI) Figs. S1 and S2).

To demonstrate strain-tuning and to quantify the corresponding spectral shift, the QD emission is studied in dependence of the applied voltage to the piezoelectric actuator. The applied voltage was varied from -400 V to +400 V, which corresponds to an electric field $F$ of -13.4 kVcm$^{-1}$ to +13.4 kVcm$^{-1}$, and results in a spectral tuning range of 0.5 nm for the present
sample, as shown in Fig. 3. Noteworthy, other samples showed a tuning range up to 4 nm when the device allows for applying higher voltages of up to ±33 kVcm\(^{-1}\) (cf. Fig. S3), however, at the risk of sample damage.

In addition to the desired wavelength shift of our piezo-controlled QD-micromesas we observe spectral fluctuation over time due to piezoelectric creep, which is most pronounced directly after a voltage change. To illustrate this point Fig. 4a) shows a systematic wavelength change of about 0.05 nm over the first 5 min after setting the piezo voltage. The creep effect decreases significantly after 30 minutes but does not vanish completely over time. This behavior is similar to earlier observations in piezo-controlled QD devices.\(^6,12,13\) In addition, we examined the relative change of the emission energies of X, XX and CX and we found that the binding energy is only slightly influenced, on a scale of 0.3 meV, by the applied strain (see SI Fig. S3). This change of binding energy is significantly smaller than values on the order of meV observed for planar QD samples with obviously better strain transfer.\(^14\) For some QDs the excitonic fine structure splitting (FSS) could be reduced from 40 µeV to 20 µeV (see SI - Fig. S3(d)). Further FSS reduction is not possible in our case. In fact, a second degree of freedom in the piezoelectric actuator would be required to fully symmetrize the distorted confinement potential, being responsible for the FSS.\(^15\)

Long-term spectral stability is one of the most important aspects of a practical single-photon source for quantum communication applications based e.g. on entanglement swapping via Bell-state measurements. Therefore, the effect of creep on the wavelength stability is an important issue to address. One can efficiently stabilize the emission wavelength, as it was reported for quantum light emitting diode\(^6\) and later also realized for deterministically fabricated InAs/GaAs QD microlense,\(^12\) by using an active optical feedback (closed-loop) algorithm. In the implemented concept the emission wavelength is monitored by Lorentzian fitting of µPL spectra taken regularly within an integration time of 0.2-1.0 s, depending on the signal intensity. The center position of the fit is compared with the target wavelength and the determined deviation initiates a re-adjustment procedure of the input voltage to shift the emission line back to the set target value. This re-adjustment is based on a PID algorithm.

The implemented wavelength stabilization is demonstrated for the CX emission of QD1 for several PID settings. In this test we set the proportional gain (PG) to 100, and the integral time (IT) parameter to 0.01 s, 0.05 s and 0.1 s to study its impact on the QD wavelength control after a voltage change applied to the piezo actuator. A graphical representation of the associated results is shown in Fig. 4b), where the following settings are characterized within a time window of 5 minutes for each setting. The corresponding parameter set and achieved
wavelength stability are shown in the Table 1. Evaluation of the recorded µPL time trances yield that best spectral stabilization with an standard deviation of the emission wavelength (energy) of 5.6 pm (4.1 µeV) could be achieved for PG = 100 and IT = 0.01 s. Moreover, we found that by increasing PG, the stabilization time decrease. However, in order to maintain the stabilization quality the IT value must be increased proportionally. We did not observe any clear dependence of the QDs spectral stability on the change of the derivative term of the PID controller.

Next, we demonstrate the CX emission lines of the two different QD-micromesas (QD1 and QD2) to being tuned in resonance and stabilized at this resonance over time by applying the optimized PID settings determined before. The time evolution of the piezoelectrically stabilized FX emission wavelength is presented in Fig. 5a), showing a standard deviation of 12 µeV for QD1 and 6 µeV for QD2, respectively. In Fig. 5b) we present µPL spectra of both QDs tuned into resonance and being stabilized at 1304.05 nm with respect to the CX emission line. Taking into account the emission linewidth (FWHM) of 47 µeV (QD1) and 33 µeV (QD2), we can extract a time integrated spectral overlap of 60-80% for the two emission lines under active PID control which reflects the efficient fine-tuning and spectral control of the QDs via the PID controlled piezo actuator.

To verify the quantum nature of emission we measured the photon-autocorrelation of the spectrally tunable CX lines of QD1 and QD2. Here, the CX transition is driven at saturation under pulsed non-resonant excitation with 80 MHz repetition rate. In Fig. 6 we present histograms of the detection events recorded in the HBT configuration representing the second-order autocorrelation function $g^{(2)}(\tau)$ which is used to evaluate the multi-photon suppression at zero time delay. First, the autocorrelation functions of QD1 and QD2 were measured without the influence of the piezo-induced strain-field emitting at different wavelengths, as shown in the upper panels of Fig. 6. The measurements show pronounced antibunching for the central peak at $\tau = 0$ ns, and the evaluation of the experimental data with the use of two-sided mono-exponential fit functions convoluted with the timing response of 50 ps of the SNSPDs used in this experiment, yields $g^{(2)}(0)_{fit} = 0.020^{+0.030}_{-0.020}$ for QD1 and $g^{(2)}(0)_{fit} = 0.052 \pm 0.030$ for QD2. When the electric field is applied to the piezo-actuator and both QDs CX emission are set to the resonant wavelength and stabilized by PID for several minutes at 1304.05 nm (the measurements were taken independently), the antibunching behavior is preserved and the corresponding fits yield $g^{(2)}(0)_{fit} = 0.040 \pm 0.030$ for QD1 and $g^{(2)}(0)_{fit} = 0.053 \pm 0.030$ for QD2, confirming that the spectral tuning has no detectable impact on the single-
photon purity of the QD-micromesas. The achieved results are very promising with regards to the target applications requiring the emission of single photons from remote quantum light sources. However, we would like to point out that the photon indistinguishability of the QD-micromesas is not yet high enough for this purpose. In fact, we examined the TPI of tunable and stabilized CX emission of QD1 under pulsed p-shell excitation in Hong-Ou-Mandel configuration. As we discuss in the SI this experiment yields a HOM visibility of (16 ± 8)%,
a post-selected visibility of (79 ± 15)%,
and the coherence time of (470 ± 85) ps (see SI Fig. 5 and Fig. 6). These values are in agreement with results achieved recently for non-tunable QD-micromesas\textsuperscript{9} which indicates that the optical quality and coherence of the 1.3 µm QD has to be improved in the future, e.g. by optimizing the SRL, in order to fully exploit their potential in advanced quantum communication applications.

In summary, we demonstrated a deterministically processed tunable QD single-photon source emitting in the telecommunication O-band at 1.3 µm. Our device consisting of a QD microlens attached to a piezoelectric actuator allows to fine-tune the QD’s emission wavelength by up to 0.5 nm via a voltage-controlled strain-field. The tuning range and an implemented closed-loop PID control system enable us to stabilize the emission energy with an accuracy (standard deviation) of up to ~4 µeV, and to hold emission lines of two remote QD-micromesas with multiphoton-suppression better than 5% in resonance with a spectral overlap of 60-80%. These results are very promising for the future implementation of long-distance quantum communication networks.

Supplementary material
See the supplementary material for information on the identification of excitonic complexes in QD1 and QD2, Hong-Ou-Mandel studies on the photon indistinguishability of QD1, and on optical properties of a second device with larger strain-tuning range.

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**Data availability**
The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Figures

Fig. 1 (a) Sample structure as grown. (b) Sample mounted in the customized spring holder of the cryostat. (c) Optical microscope image of the sample after resist development. (d) SEM image of the close-up processed sample showing the mapping area with the two mesas hosting QD1 and QD2. (e) SEM image close-up of the investigated mesa hosting QD1.

Fig. 2 (a) CL map of the lithography step at 10 K with QD1 and QD2 circled. The spectral range of 1300 nm to 1305 nm is depicted. (b) µPL spectra of the corresponding QD1 and QD2 taken after processing was completed.
Fig. 3. Energy tuning of the CX emission line of QD1 (black to blue). An energy shift of 380 μeV (0.5 nm) was observed due to changing the electric field applied to the piezoelectric actuator from -13.4 kV/cm to +13.4 kV/cm. The CX emission line of QD2 without applied electric field (red) is within the energetic tuning limits of QD1.

Fig 4. (a) Impact of the piezoelectric actuator's creep on the wavelength of the CX emission line of QD1 over time. (b) PID stabilization tests on QD1 (see Table 1 for the summary).

| PID settings (prop. Gain = 100) | PID₁ | PID₂ | PID₃ |
|----------------------------------|------|------|------|
| PID integral time (s)            | 0.01 | 0.05 | 0.1  |
| standard deviation (μeV)         | 4.12 | 4.45 | 5.26 |
| stabilization time (s)           | 30   | 50   | 80   |

Table 1. Quantified results of the emission wavelength stability for various PID integral times evaluated in terms of a standard deviation of emission energy and stabilization time required for the adjustment.
Fig. 5. (a) $\mu$PL spectra of two deterministic QDs set in resonance via applied piezoelectric strain field and (b) measurements data of emission wavelength in time to quantify the stabilization.

Fig. 6. (a) autocorrelation experiment performed on charged exciton of QD1 and (b) QD2 in case of “on” and “off” PID controller of the piezoelectric actuator which is used for stabilization of emission wavelength.
Supplementary Materials: Deterministically fabricated strain-tunable quantum dot single-photon sources emitting in the telecom O-band

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1. Identification of the excitonic complexes of QD1 and QD2

The excitonic states of the QDs were identified by evaluating power and polarization dependent micro-photoluminescence (µPL) series, as shown in Fig. S1 for QD1. The QD was non-resonantly excited by a continuous-wave (cw) diode laser at 785 nm. Already in the low excitation power regime the neutral (X) and charged exciton (CX) are visible. The biexciton (XX) becomes visible in the high-power regime. With increasing excitation power $P$ the µPL intensity $I$ of X and CX increase proportionally to the excitation power: $I \sim P$. Whereby for the XX the relationship of $P$ and $I$ scales as: $I \sim P^2$. Additionally, to distinguish between the X and CX complex a polarization series in linear basis was performed. The CX complex shows no fine structure splitting (FSS), as expected due to no exchange interactions between electrons and holes. An FSS of approx. 50 µeV was determined for the X state. The line at about 0.95 meV does not show noticeable FSS and most probably corresponds to charged biexcitonic state of QD1. The same analysis was performed for QD2 as presented in Fig. S2. Here the X shows an FSS of 90 µeV.

![FIG S1. Emission properties of QD 1: µPL spectra in dependence on excitation power (left panel) and polarization angle dependence of X and CX (right panels).](image-url)
FIG S2. Emission properties of QD 2: μPL spectra in dependence on excitation power (left panel) and polarization angle dependence of X and CX (right panels).

2. Optical properties of a second device with laser strain-tuning range
A second device (B), similar to device A (whose results are presented in the main text), was fabricated, using QD material of the same wafer and following the processing steps described in the main text. Fig S3 presents a summary of the main measurements performed on this second device. Analogue to device A, power and polarization dependent μPL series were performed for a selected QD-mesa (QD3) (see Fig. S3 a-b)) to identify the different excitonic complexes. QD3 shows an FSS of 60 μeV which is similar to the values observed for sample A.

The bonded piezoelectric actuators of device A and B are of the same material (PIN-PMN-PT). Only the piezoelectric actuator as well as the bonded GaAs membrane of device B are twice the size compared to device A. With device B an overall wavelength tuning of 2.9 meV (4.2 nm) could be achieved by tuning the applied electric field in the range of ±33.3 kV/cm (see Fig. S3c)). Comparing only the tuning range for an applied electric field of ±13.3 kV/cm device A allowed for a 0.38 meV (0.5 nm) and device B for a 1.5 meV (2.16 nm) wavelength tuning. Different QDs of one device show similar wavelength shifts for a given applied electric field. However, the maximum tuning range differs for the two devices, which may be due to minor variations in the QD material composition or more likely to processing related divergences. The quality of stress transmission from the piezoelectric actuator to the position of the QDs crucially depends on the gold bonding quality, here the difference in size of the bonded membranes of devices A and B could play a part.
In Fig. S3 d)) we present the FSS and the relative phase of the linearly polarized states of QD3 in dependence of the voltage applied to the piezoelectric actuator. The FSS could be reduced from 60 µeV to a minimum of 20 µeV. Here, the non-zero FSS indicates that the applied strain-field is not accurately aligned to the high symmetry crystal axes [110] or [1-10]. A partial inversion of the polarized states is observed. The polarization of the exciton transition is overall rotated by 65°. Noteworthy, the interdependence between FSS and the relative phase agree well with the theoretical analysis in Ref. [1] under variation of the biaxial strain applied to the QD.

Finally, in Fig. S3 e) the emission energy of X ($E_x$) and the binding energies ($\Delta E$) of the CX and XX states are plotted vs. the applied voltage. The binding energies of XX and CX, defined as the difference of emission energies $\Delta E_{XX/CX} = E_X - E_{XX/CX}$, increase under compressive stress (kV/cm > 0) and decrease with tensile stress (kV/cm < 0) in all studied QDs. This observation of an increasing (decreasing) $\Delta E$ can be traced back to the effect of an increase (decrease) of the electron-hole overlap and an associated change of the electron-hole attraction when an in-plane compressive (tensile) biaxial strain is applied.1

FIG S3. Optical and strain-tuning characteristic of QD3 stemming from sample. Excitation power (a), polarization, and piezo tuning (c) µPL series. The indicated electric field range is associated with an applied voltage of -33 to 33 kV/cm to the piezo-actuator, leading to a tuning range of approx. 4 nm. d) Dependence of the FSS and the polarization phase vs. the applied electric field. e) Exciton energy, and CX and XX binding energy as function of the applied electric field.

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3. Hong-Ou-Mandel studies on photon indistinguishability of QD1

To analyze the photon indistinguishability of QD1 we performed pulsed two-photon interference (TPI) measurements using a fiber-based HOM setup with an unbalanced Mach-Zehnder (MZI) interferometer on the excitation side and a complementary MZI on the detection side. The relative optical path delay is 4 ns resulting in clusters of five peaks in the correlation histogram every 12.5 ns for the given laser repetition rate of 80 MHz. The employed fit function is based on a sum of Lorentzians which are temporally shifted from one another in time in steps of about 4 ns. The raw data, the corresponding fit and the fit decomposition are presented in Fig. S4. For a deeper insights into the theoretical resulting histograms see Ref. 2 and for a detailed mathematical description of the applied fit function see Ref. 3.

The measured data is slightly unbalanced and therefore to determine the visibility we use only the central peak area and the areas of the first side peaks of the copolarized HOM histograms. Using the central peak areas $A_0$ and $A_{00}$, where indices “0” and “00” corresponds to the HOM central peak and HOM dip minimum, respectively, the TPI visibility can be determined by

$$V = \frac{A_0 - (A_0 + A_{00})}{A_0} \times 100\% = (11.7 \pm 6.7)\%,$$

Next, we define the peak area of the first side peak as an average: $A_1 = (A_{1,\text{L}} + A_{1,\text{R}})/2$ and the TPI visibility is given by

$$V = \frac{(2/3)A_1 - (A_0 + A_{00})}{(2/3)A_1} \times 100\% = (21 \pm 14)\%.$$

Based on this evaluation we obtain an average value for the photon indistinguishability of $V = (16 \pm 8)\%$. This value agrees with $V = (12 \pm 4)\%$ reported in Ref. 3 for a very similar device with back-side Au mirror but without piezo-element. We attribute the rather low indistinguishability to spectral jitter due to charge fluctuation in the QD environment including the strain-reducing layer. This highlights again that further growth optimization is necessary to improve the photon indistinguishability of the long-wavelength InGaAs QDs, where HOM studies are a very efficient tool to evaluate the quantum-optical properties of these emitters.

To obtain additional insight into the photon indistinguishability and the related coherence properties of emission we apply the above-mentioned fit function, to determine the post-selected visibility. For this purpose we use the value at zero time delay given by the fit function $f(0)$ (see Fig. S4 b)) with respect to the expected maximum in case of distinguishable
photons, which could be approximated by the same function neglecting the “00” HOM dip contribution \( f'(0) \) (see Fig. S4 b)). Then the post-selected visibility \( V_{ps} \) at \( \tau = 0 \) is given by

\[
V_{ps} = \frac{f(0) - f'(0)}{f(0)} \times 100\% = (85 \pm 8)\%.
\]

FIG S4. TPI histograms measured for the CX emission of QD1 under pulsed p-shell excitation for co-polarized configuration. The HOM-effect is proven by the highly reduced coincidences at zero-time delay. The red trace corresponds to the applied fit function based on a sum of Lorentzian peak functions. In part (b) the decomposition into individual peaks is shown in order to determine post selected visibility from \( f(\tau=0) \) and \( f'(\tau=0) \). In the fit we consider an uncorrelated background of 0.67.

A further analysis of the central dip of the HOM histogram for parallel polarized photons allows for an estimation of the coherence time \( \tau_c \), which is characterised by the width of this central dip (cf. Fig S5). The central dip is fitted by a double exponential decay function and convoluted with the response function of the detectors (time jitter \( \sim 50 \) ps). The first side peaks at ± 4 ns were as well considered for the fit, in the form of their previous decomposed Lorentzian functions. For the mathematical description see Ref. 2. With the visibility \( V \) fixed to 1 and the three free fitting parameters lifetime of spontaneous emission \( \tau_1 \), the dephasing time \( \tau_{deph} \) and the background \( y_0 \) we obtained \( \tau_1 = (1.54 \pm 0.05) \) ns and \( \tau_{deph} = (0.55 \pm 0.08) \) ns for a background \( y_0 \ll 0.01 \). The correspondent fit is depicted in Fig. S4. Taking dephasing into account and therefore following the relation \( \frac{1}{\tau_{deph}} = \frac{1}{\tau_c} - \frac{1}{2\tau_1} \), we obtain a coherence time of \( \tau_c = (0.47 \pm 0.08) \) ns.
The post-selection approach naturally leads to higher TPI visibility which is essentially limited by the temporal resolution of the used single-photon detectors. In order to enlarge the low visibility without post-selection and to produce high-purity triggered indistinguishable single photons, it is necessary to reduce the dephasing rate and timing jitter e.g. by s-shell resonant excitation or by reducing charge noise by electric control in contacted devices. Furthermore, further optimization of the strain-reducing layer to reduce the number of charged defect states, leading to spectral jitter, could improve the quantum optical quality of the devices.

FIG S5. Close-up of the HOM histogram for parallel polarized photons. The TPI dip is fitted by a double exponential decay function taking the response function of the SNSPDs into account, see text for details.

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