Spectral control of deterministically fabricated quantum dot waveguide systems using the quantum confined Stark effect

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ABSTRACT
Quantum photonic circuits with integrated on-demand quantum emitters can act as building blocks for photonic gates and processors with enhanced quantum functionality. To scale up such quantum devices to larger and more powerful systems, eventually reaching the quantum advantage, the scalable integration of many emitters with identical emission wavelengths is of utmost importance. Here, we report on the deterministic integration of self-assembled quantum dots (QDs) in waveguide structures by means of in situ electron beam lithography (EBL). Applying external bias voltages to the p-i-n-doped and electrically contacted quantum circuits allows for spectral fine-tuning of the QDs via the quantum confined Stark effect. We achieve a tuning range of $(0.40 \pm 0.16)$ nm, which together with a spectral pre-selection accuracy of $(0.2 \pm 1.6)$ nm in the in situ EBL process is on average large enough to tune individual QDs into resonance. Thus, deterministic QD integration with spectral pre-selection in conjunction with Stark tuning of the QD emission wavelength is an attractive combination that has high potential to enable the scalable fabrication of integrated quantum photonic circuits in the future.

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I. INTRODUCTION
Waveguides with deterministically integrated emitters of single and indistinguishable photons are key elements of integrated quantum photonic circuits (IQPCs). In order to be able to implement a powerful optical quantum computer with these non-classical light sources, the photon-coupling efficiency of the emitters to waveguides must be maximized. In addition, it must be ensured that all sources emit photons of identical wavelengths in order to enable photon–photon interactions through the Hong–Ou–Mandel (HOM) effect, which is at the heart of, for instance, the boson sampling concept. Of particular interest are solid-state quantum emitters that provide single photons, in principle, on demand and with a high emission rate. Among them are defect centers in solid-state materials such as diamond and SiC, quantum emitters in transition metal dichalcogenides, and self-assembled quantum dots (QDs). In fact, QDs feature close-to-ideal emission properties in terms of the emission rate, multi-photon suppression, and photon indistinguishability. However, their random character with respect to the position and emission wavelength hinders device integration with a high yield and scaling up from single-emitter proof-of-principle experiments to complex and scalable implementations of real-world quantum systems such as photonic quantum processors with many-photon input states. The strong demand for advanced fabrication technologies for QD quantum devices with a high process yield triggered the development of deterministic nanofabrication technologies. Most interesting are in situ lithography technology platforms that allow for the pre-selection of quantum emitters and their controlled integration into high-performance nanophotonic devices such as single-photon sources based on micropillars and microlenses. Similarly, large scale QD imaging in combination with standard electron
beam lithography (EBL) has been used to deterministically realize high-performance quantum light sources based on circular Bragg gratings.24,25 A very precise and flexible deterministic nanotechnology platform is in situ electron beam lithography (EBL).26 This concept uses low-temperature cathodoluminescence (CL) mapping to select QDs with suitable emission properties in terms of intensity and wavelength and uses EBL in the same system to define the target photon structure aligned with a few 10 nm accuracy to the selected QD.27 This technique has been applied for the deterministic fabrication of bright single-photon sources28,29 and waveguide systems30,31 based on single QDs. Despite the high spectral resolution of the in situ EBL process better than 0.1 nm, changes in the local charge carrier configuration in subsequent cool-down circles can lead to jumps in the QD emission wavelength of up to \(\sim 1\) nm. In order to bring the pre-selected QDs into resonance in scalable quantum circuits on the necessary scale of the homogeneous linewidth \((\sim 1\ \mu eV)\), additional spectral fine-tuning capabilities for the local control of individual QDs within a spectral range on the order of 1 nm are desirable.

Spectral fine-tuning can be implemented using different approaches. In the case of temperature tuning, changing the bandgap of the semiconductor material,32 usually all QDs of a sample are detuned in the same way and the phonon interaction of the QDs increases, leading to a reduction in the photon indistinguishability.33 Detuning via magnetic fields also influences all QDs of a sample simultaneously and is technically complex.34,35 An attractive approach for wavelength tuning is to apply external strain via piezoelectric actuators. In this way, tunable single-photon sources could be realized very successfully.36-38 This approach was recently also transferred to waveguide-coupled QDs, although only the detuning of a single QD was shown.39 As in the approaches mentioned above, the strain caused by piezoelectric actuators usually affects the entire sample, which is why the independent tuning of several QDs on the same sample has not yet been proven.

The most promising approach to individually adjust the emission wavelength of several QDs on a chip is the control by electrical fields via the quantum confined Stark effect (QCSE).27 If QDs are integrated into the intrinsic layer of a p-i-n diode, individual p and n contacts can be lithographically implemented for each QD, and the QD emission energy can be tuned independently. In p-i-n-doped samples with suitable tunnel barriers, a spectral detuning of \(\sim 30\) nm could be achieved by applying an external voltage.38 The integration of several contacts allowed Peruzzela et al.38 to tune two QDs, which are in the input ports of a \(2 \times 2\) MMI beam splitter, into resonance by the QCSE. Ellis et al.39 succeeded in coupling a p-i-n-doped single-photon source chip with independent contacts and a waveguide network chip to one another by gluing. With this, they demonstrated the indistinguishability of photons from two different QDs in an integrated waveguide experiment. Both works, however, relied on finding randomly integrated QDs that have a similar emission energy.

In this work, we deterministically realize and study Stark-tunable QD-waveguide systems. The self-assembled QDs are embedded in the intrinsic region of a p-i-n diode. Using in situ EBL, we deterministically integrate multiple QDs into linear monomode waveguides, which are electrically contacted. Biasing the electrical contacts allows us to control the emission wavelength of single integrated QDs and to tune QDs into spectral resonance. In this way, the prerequisites are created for the scalable integration of several single-photon emitters with identical emission into complex IQPCs with enhanced functionality.

II. DEVICE DESIGN AND FABRICATION

A. Device design

We first discuss the requirements that must be met by the design of the p-i-n-QD sample so that both waveguides with electrical detuning and the integration of QDs via in situ EBL in the GaAs–AlGaAs material system are possible. Overall, the sample design must meet the following requirements: (a) enable the fine-tuning of the QD emission wavelength by the QCSE, (b) be compatible with the in situ EBL manufacturing process, (c) ensure high QD-waveguide coupling, and (d) provide strong wave guiding. This leads to a layer design that is composed of a GaAs p-i-n diode with AlGaAs tunnel barriers, which also functions as a waveguide core, and an AlGaAs cladding layer as presented in Fig. 1(a). The thickness and composition of each layer of the sample affect several of the aforementioned requirements. In order to meet all requirements, careful compromises have to be made in the design of the sample. For instance, for strong waveguiding and efficient QD mode coupling, a high refractive index contrast between the core and the cladding is necessary, which can be achieved by high Al concentrations in the cladding. However, the higher the concentration, the faster the AlGaAs oxidizes, which degrades the waveguide quality. Another aspect to be considered is the barriers below and above the active QD layer. They prevent charge carriers from tunneling out of the QD, which becomes more efficient with their thickness and Al concentration and is essential for spectral tuning by the QCSE. On the other hand, the thinner they are and the lower the Al concentration, the higher the effective refractive index of the waveguide core and the better the waveguiding and the QD mode.

![FIG. 1. (a) Layer structure of the sample. Doping concentrations and layer thicknesses are mentioned in the text. (b) FEM grid and exemplary SEM image of a fabricated waveguide facet (inset). (c) Calculated field intensities of the fundamental TE mode for a target wavelength of 940 nm. The TM mode is not guided.](https://scitation.aip.org/content/aip/journal/aplphotonics/6/5/10.1063/5.0050152)
coupling. Concerning the central GaAs layer, which includes the active region with QDs, it is necessary to note that the thinner the layer, the more efficiently the barriers prevent charge carriers from tunneling out of the QDs. Contrarily, the thickness of the GaAs QD layer has a decisive influence on the cathodoluminescence (CL) excitation efficiency in the in situ EBL process (described below): The AlGaAs barriers prevent charge carriers that are generated by the electron beam outside the GaAs QD layer from diffusing to the QD. A thick GaAs layer is therefore essential so that sufficient electron–hole pairs are generated in the vicinity of the QD so that a sufficiently strong CL signal for the QD localization can be detected. The GaAs layer must also be placed approximately at the level of the maximum of the TE fundamental mode in order to achieve a high QD mode coupling. The uppermost GaAs layer supports waveguiding. However, for a very thick cladding layer, the mode maximum of the TE fundamental mode shifts upward, which leads to poor QD mode coupling. Finally, the doping concentrations need to be optimized for an optimum balance between good electrical control of the QD properties via the QCSE and low free carrier absorption.

Based on these considerations, the layer structure was optimized using the finite element method (FEM) solver JCMSuite and is presented in Fig. 1(a) (layer thicknesses are mentioned along with the sample growth in Sec. II B). The results of FEM simulations of the fundamental TE mode for an emission wavelength of 940 and 550 nm wide and only 110 nm deep etched single-mode waveguides are depicted in Fig. 1(c). The simulation grid and an exemplary scanning electron microscopy (SEM) image of the waveguide facet are shown in Fig. 1(b). The low-temperature refractive indices extrapolated from Ref. 41, \( n(\text{GaAs}) = 3.49, n(\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}) = 3.25, \) and \( n(\text{Al}_{0.9}\text{Ga}_{0.1}\text{As}) = 2.94, \) result for the fundamental TE and TM mode in an effective refractive index of \( n_{\text{eff}} = 2.99 \) (2.93) for TE00 (TM00). The effective refractive index \( n_{\text{eff}} \) of the TM mode is lower than the refractive index of the cladding with \( n(\text{Al}_{0.9}\text{Ga}_{0.1}\text{As}) = 2.94, \) and no TM modes are guided. The QD coupling efficiency is calculated from the overlap of a dipole emission with the waveguide mode and is \( \sim 8\% \) per direction. This value is rather low in the present proof-of-principle case and can be increased in the future by including, for instance, lateral Bragg gratings for enhanced light–matter interaction. We would like to note that our waveguide design is not optimized for strong waveguiding.

B. Sample growth and device fabrication

The heterostructure sample was grown via metal organic chemical vapor deposition (MOCVD) on a Si-doped GaAs (100) wafer using TMGa, TMAl, and TMIn for group III, AsH3 and TBA for group V materials as well as SiH4 and DEZn for doping. All layers below the QDs were grown at an ambient temperature of 700 °C, the ones above the QDs were grown at 615 °C, and the QDs themselves were grown at 500 °C. The first layers deposited are a 100 nm thick \( \text{Al}_{0.01}\text{Ga}_{0.99}\text{As} \) to \( \text{Al}_{0.9}\text{Ga}_{0.1}\text{As} \) grading layer followed by 1900 nm of \( \text{Al}_{0.9}\text{Ga}_{0.1}\text{As} \) and 15 nm of GaAs:Si (doping concentration of \( 5 \times 10^{18} \) cm\(^{-3}\)), all serving as cladding for the waveguide structure. The layers that later form the waveguide core start with 5 nm of intrinsic GaAs and are followed by a lower 40 nm and upper 30 nm thick \( \text{Al}_{0.3}\text{Ga}_{0.7}\text{As} \) carrier diffusion barrier layer enveloping a 10 nm thick layer of GaAs containing the InGaAs QD layer in its center. The QDs were formed by depositing 1.7 monolayers of nominal \( \text{In}_{0.6}\text{Ga}_{0.4}\text{As} \). Above the upper carrier diffusion barrier, we grew another intrinsic 5 nm layer of GaAs before capping our sample with 55 nm of GaAs:Zn (doping concentration of \( 3 \times 10^{19} \) cm\(^{-3}\)). The described layer structure is pictured in Fig. 1(a).

In the following we describe how to contact the p–n diode so that it is compatible with the in situ EBL process. The challenge here is to design the contacts in such a way that the sample can first be coated with EBL resist and then contacted through the coating. Furthermore, after the in situ EBL waveguide integration, the sample should have several individual contacts with which QDs can be detuned independently. In order to keep the contacting process as simple as possible, we chose a planar back-side n-contact via the \( n \)-doped GaAs substrate. The design of the \( p \)-top contact is shown schematically in Fig. 2(a). The large yellow area is a \( 1800 \times 2700 \) \( \mu \)m\(^2\) bond pad. After the sample has been spin-coated with electron beam resist, the macroscopic pad can be contacted with a fine needle that pierces through the resist and is in thermal contact with the cryostat. The entire sample can then be biased via the macroscopic pad (enabled by the high \( p \)-doping concentration) during the in situ EBL process. Overall, the developed contact design enables us to individually address different WG-sections with deterministically integrated QDs for spectral Stark tuning. In order to individually bias QDs after lithography, next to the macroscopic gold pad, we added \( 300 \times 300 \) \( \mu \)m\(^2\) sized smaller pads, which can be isolated from the macroscopic pad by etching through the p–p-doped layers and can be contacted individually by wire-bonds.

The contacts are made as follows: For the n-contact, 20 nm nickel, 100 nm gold-germanium, and 300 nm gold are deposited on the back of the sample by thermal evaporation. The \( p \)-top contact is defined in a lift-off process with optical lithography. 20 nm titanium, 50 nm platinum, and 250 nm gold are applied to the sample by electron beam evaporation. The isolation trenches between macroscopic and smaller pads are also defined by optical lithography and etched 140 nm deep into the semiconductor by inductively coupled plasma reactive-ion etching (ICP-RIE).

Subsequent to contact formation, the sample is coated with ~100 nm CSAR 62 EBL resist before mounting it onto the cold-finger of the low-temperature in situ EBL system. A row of gold bond pads and the pierced copper needles establish the electrical connection to the p–p-top contact. An exemplary current–voltage (I–V) characteristic at 7 K is shown in Fig. 2(b). The sample shows a slightly asymmetric I–V behavior with low current flow in the reverse direction up to about ~2 V and an onset of current flow at about 2.0 V in the forward direction. In situ EBL is performed at 7 K, with a bias voltage of 0.9 V being the optimal operating point in relation to emission intensity and current flow. For a combination of 15 kV acceleration voltage and 0.25 nA beam current with an integration time of 50 ms per pixel and an effective pixel size of \( (500 \times 500) \) \( \mu \)m\(^2\), CL mapping with a dose of 5 mC is performed, which enables a QD localization accuracy better than 10 nm per spatial axis. An exemplary CL intensity map is presented in Fig. 2(c). The areal QD density is, on the one hand, large enough to find almost resonant QDs and, on the other hand, sufficiently low so that still individual QDs can be localized. To illustrate this aspect, two nearly resonant QDs are selected.
FIG. 2. (a) Schematic view of the sample design and contact layout. (b) I–V characteristics of the planar, unpatterned sample at 7 K. (c) 2D CL map recorded at 0.9 V bias voltage. The color coded (in linear scale) intensity is based on the wavelength interval filtered, which is marked by green vertical lines in (d). Spatially localized CL detected from two almost resonant QDs (QD1 and QD2) as marked by white circles. (d) CL spectra of QD1 and QD2 marked in panel (c). (e) Microscope image of fully processed waveguides, which were fabricated by in situ EBL. All waveguides are connected via extensions to the top bond pads. (f) Enlarged view from (e) in which the positions of QD1 and QD2 are indicated by black circles.

in the CL map (indicated by white circles), where the intensity of the map was filtered to the wavelength range $[(929.5 \pm 1.0) \text{ nm}]$ as marked by the green vertical lines in Fig. 2(d), which shows the corresponding CL emission spectra. The peak positions of the two QDs differ by $\sim 1$ nm.

After QDs are located in CL maps, 550 nm wide waveguides are written at their locations with a constant exposure of 40 mC/cm$^2$. Fully processed QD-waveguide structures can be seen in Figs. 2(e) and 2(f). The QDs were integrated deterministically by in situ EBL as described in detail in Ref. 26. Figures 2(e) and 2(f) present waveguides with a height of 110 nm in which two QDs [QD1 and QD2 from panels (c) and (d)] with very similar wavelength were integrated. The ends of the waveguides are connected to different bond pads. By integrating two QDs with similar wavelength in the same waveguide, we intend to demonstrate the good control and high process yield of our deterministic device processing. Eventually, in order to realize complex quantum circuits with high quantum functionality, it is important to integrate the Stark-tunable QD into different waveguide sections.

III. OPTICAL DEVICE CHARACTERIZATION AND SPECTRAL STARK TUNING OF QUANTUM DOT–WAVEGUIDE SYSTEMS

After processing, the deterministic integration of the QDs into the waveguide circuits is investigated by means of confocal microphotoluminescence (μPL) spectroscopy at 10 K under non-resonant excitation at 660 nm. Figure 3(a) shows a corresponding bias-voltage dependent series from QD2. Focusing the laser to the previously (in the in situ EBL process) determined position of QD2, we observe sharp single-QD emission lines with resolution limited linewidths of 40 μeV and the most pronounced feature at about 927 nm in the 2D PL intensity map of Fig. 3(a). This emission is associated with the neutral exciton (identified by polarization-resolved measurements), which deviates in wavelength by 2.3 nm from $\approx 929.5$ nm, which was observed during in situ EBL in Fig. 2(d). This spectral deviation is most probably caused by charged surface states leading to band-bending at the QD position. In addition, we also often observe the spectral shift on the order of 1 nm caused...
by different charge configurations in subsequent cooling cycles. Overall, the good spatial and spectral agreement confirms the successful deterministic waveguide integration of QD2. For a statistical evaluation of the process yield, all 52 pre-selected QDs of the sample are checked for their deterministic integration in the same way. QDs that deviate by more than 3 nm from the wavelength of the CL mapping are considered to be non-deterministically integrated. This way, a deterministic integration yield of 73% is determined. The QD emission wavelength, which is measured in µPL, changes on average by Δλ = (0.2 ± 1.6) nm as compared to the in situ EBL mapping.

Next, we evaluate the spectral control of QD emission by using the QCSE in more detail. As can be seen in Fig. 3(a) for increasing voltages V, the emission shifts to lower wavelengths. This blue shift agrees qualitatively with the observations in Refs. 13, 40 and 43 in p-i-n diodes and confirms that the wavelength shift is due to electrical control by the QCSE. A quadratic curve fit to the QCSE in more detail. As can be seen in Fig. 3(a) for increasing voltages V, the change in the emission energy of the exciton (X) from (a) vs the calculated electric field strength at the location of the QD. The experimental trend is modeled with a quadratic curve fitting. (b) The change in the emission energy of the exciton (X) from (a) vs the calculated electric field strength at the location of the QD. The experimental trend is modeled with a quadratic curve fitting. (c) Emission intensity (integrated intensity) vs the applied voltage.

FIG. 3. (a) Bias-dependent µPL series of QD2 (the PL intensity is color coded in linear scale). The spectral detuning of the narrow emission lines due to the QCSE under increasing voltage can be clearly seen. The emission lines are blue shifted by ~2 nm compared to the CL spectrum obtained during in situ EBL processing [see Fig. 2(b)]. (b) The change in the emission energy of the exciton (X) from (a) vs the calculated electric field strength at the location of the QD. The experimental trend is modeled with a quadratic curve fitting. (c) Emission intensity (integrated intensity) vs the applied voltage.
the bias-dependent spectral characteristics observed in Fig. 4(c) indicate different charge environments for QD3 and QD4, which change with the applied bias voltage, possibly due to charging/discharging of defect states at the nearby etched surface. We attribute the noncontinuous tuning behavior observed in Fig. 4(d) to these different and bias-dependent charge environments. Overall, this experiment should be treated as a proof-of-principle only. Further work will focus on integrating Stark-tunable QDs in electrically isolated input sections, e.g., to the input ports of a multi-mode interference beam splitter in an on-chip Hong–Ou–Mandel configuration.

IV. CONCLUSION

In summary, we report on the deterministic waveguide integration of QDs and their spectral control via the QCSE. For this purpose, a p-i-n diode sample design was developed, which allows for Stark tuning of QD-WGs and is compatible with the in situ EBL process. This way, we were able to integrate preselected QDs into linear monomode WGs with a high process yield of 73%. Within a statistical analysis, we found that the emission lines of deterministically integrated QDs shift on average by $\Delta \lambda = (0.2 \pm 1.6)$ nm when compared to the spectral features during fabrication and for the final device. We further showed that the emission wavelength of deterministically integrated QDs can be detuned within a range of $(0.40 \pm 0.16)$ nm. Beyond that, we showed that two QDs, which were integrated into a waveguide device via in situ EBL, could be successfully tuned into resonance with each other with the help of the QCSE. These results pave the way for the scalable integration of multiple QDs emitting individual and indistinguishable photons into quantum photonic circuits for applications in photonic quantum technologies in the future.

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DATA AVAILABILITY

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

REFERENCES

1. C. P. Dietrich, A. Fiore, M. G. Thompson, M. Kamp, and S. Höfling, "GaAs integrated quantum photonics: Towards compact and multi-functional quantum photonic integrated circuits," Laser Photonics Rev. 10, 870–894 (2016).
2. A. W. Eshlaari, W. Pernice, K. Srinivasan, O. Benson, and V. Zwiller, "Hybrid integrated quantum photonic circuits," Nat. Photonics 14, 285–298 (2020).
3. S. Rodl and S. Reitzenstein, "Integrated nanophotonics for the development of fully functional quantum circuits based on on-demand single-photon emitters," APL Photonics 6, 010901 (2021).
4. M. Arcari, I. Sollner, A. Javadi, S. L. Hansen, S. Mahmoodian, J. Liu, H. Thyregod, E. H. Lee, J. D. Song, S. Stobbe, and P. Lodahl, "Near-unity coupling efficiency of a quantum emitter to a photonic crystal waveguide," Phys. Rev. Lett. 113, 096603 (2014).
5. M. Tillmann, B. Dakić, R. Heilmann, S. Nolte, A. Szameit, and P. Walther, "Experimental boson sampling," Nat. Photonics 7, 540–544 (2013).
6. M. A. Broome, A. Fedrizzi, S. Rahimi-Keshari, J. Dove, S. Aaronson, T. C. Ralph, and A. G. White, "Photonic boson sampling in a tunable circuit," Science 339, 794–798 (2013).
7. A. W. Schell, J. Kaschke, J. Fischer, R. Henze, J. Wolters, M. Wegener, and O. Benson, "Three-dimensional quantum photonic elements based on single nitrogen vacancy-centres in laser-written microstructures," Sci. Rep. 3, 1577 (2013).
8. I. Aharonovich, D. Englund, and M. Toth, "Solid-state single-photon emitters," Nat. Photonics 10, 631–641 (2016).
9. P. Tonndorf, R. Schmidt, R. Schneider, J. Kern, M. Buscema, G. A. Steele, A. Castellanos-Gomez, H. S. J. van der Zant, S. Michaelis de Vasconcellos, and R. Bratschitsch, "Single-photon emission from localized excitons in atomically thin semiconductors," Optica 2, 347 (2015).
10. S. Ren, Q. Tan, and J. Zhang, "Review on the quantum emitters in two-dimensional materials," J. Semi. Cond. 40, 071903 (2019).
11. Y. Arakawa and M. J. Holmes, "Progress in quantum-dot single photon sources for quantum information technologies: A broad spectrum overview," Appl. Phys. Rev. 7, 021309 (2020).
12. A. Schlehahn, A. Thoma, P. Munnely, M. Kamp, S. Höfling, T. Heindel, C. Schneider, and S. Reitzenstein, "An electrically driven cavity-enhanced source of indistinguishable photons with 61% overall efficiency," APL Photonics 1, 011301 (2016).
13. F. Liu, A. J. Brash, J. O’Hara, L. M. P. Martins, C. L. Phillips, R. J. Coles, B. Royall, E. Clarke, C. Bentham, N. Priligjaz, I. E. Itskovich, L. R. Wilson, M. S. Skolnick, and A. M. Fox, "High purcell factor generation of indistinguishable on-chip single photons," Nat. Nanotechnol. 13, 835–840 (2018).
14. L. Schweickert, K. D. Jons, K. D. Zeuner, S. F. Cove da Silva, H. Huang, T. Leitner, M. Reinell, J. Zich, R. Trotta, A. Rastelli, and V. Zwiller, "On-demand generation of background-free single photons from a solid-state source," Appl. Phys. Lett. 112, 093106 (2018).
15. N. Somaschi, V. Giesz, L. De Santis, J. C. Loredo, M. P. Almeida, G. Hornecker, S. L. Portalupi, T. Grange, C. Antón, J. Demory, C. Gómez, I. Sagnes, N. D. Lanzillotti-Kimura, A. Lemaître, A. Aufseves, A. G. White, L. Lancio, and P. Senellart, "Near-optimal single-photon sources in the solid state," Nat. Photonics 10, 340–345 (2016).
16. X. Ding, Y. He, Z.-C. Duan, N. Gregersen, M.-C. Chen, S. Undleben, S. Maier, C. Schneider, M. Kamp, S. Höfling, C.-Y. Lu, and J.-W. Pan, "On-demand single photons with high extraction efficiency and near-unity indistinguishability from
a resonantly driven quantum dot in a micropillar," Phys. Rev. Lett. 116, 020401 (2016).

17) J. Liu, R. Su, Y. Wei, B. Yao, S. F. C. da Silva, Y. Yu, J. Iles-Smith, K. Srinivasan, A. Rastelli, J. Li, and X. Wang, "A solid-state source of strongly coupled photons with high brightness and indistinguishability," Nat. Nanotechnol. 14, 586–593 (2019).

18) H. Wang, J. Qin, X. Ding, M.-C. Chen, S. Chen, X. You, Y.-M. He, X. Jiang, L. You, Z. Wang, C. Schneider, J. J. Renema, S. Höfling, C.-Y. Lu, and J.-W. Pan, "Boson sampling with 20 input photons and a 60-mode interferometer in a 104-dimensional Hilbert space," Phys. Rev. Lett. 123, 250503 (2019).

19) A. Dousse, L. Lanco, J. Suffczynski, E. Semenova, A. Miard, A. Lemaître, I. Sagnes, C. Roblin, J. Bloch, and P. Senellart, "Controlled light-matter coupling for a single quantum dot embedded in a pillar microcavity using far-field optical lithography," Phys. Rev. Lett. 101, 267404 (2008).

20) M. Gschrey, F. Gericke, A. Schüller, R. Schmidt, J.-H. Schulze, T. Heindel, S. Rodt, A. Strittmatter, and S. Reitzenstein, "In situ electron-beam lithography of deterministic single-quantum-dot mesa-structures using low-temperature cathodoluminescence spectroscopy," Appl. Phys. Lett. 200, 251113 (2013).

21) G. Undleber, Y. M. He, S. Gerhardt, M. Auer, C. Y. Lu, J. W. Pan, N. Gregersen, M. Kamp, C. Schneider, and S. Höfling, "Highly indistinguishable on-demand resonance fluorescence photons from a deterministic quantum dot micropillar device with 74% extraction efficiency," Opt. Express 24, 8539–8546 (2016).

22) M. Gschrey, A. Thoma, P. Schnauber, M. Seifried, R. Schmidt, W. Buhlfeif, L. Krüger, J. H. Schulze, T. Heindel, S. Burger, F. Schmidt, A. Strittmatter, S. Rodt, and S. Reitzenstein, "Highly indistinguishable photons from deterministic quantum-dot microcavities utilizing three-dimensional in situ electron-beam lithography," Nat. Commun. 6, 8662 (2015).

23) S. Sapienza, M. Davanço, A. Badolato, and K. Srinivasan, "Nanoscale optical positioning of single quantum dots for bright and pure single-photon emission," Nat. Commun. 6, 7833 (2015).

24) M. Gschrey, R. Schmidt, J.-H. Schulze, A. Strittmatter, S. Rodt, and S. Reitzenstein, "Resolution and alignment accuracy of low-temperature in situ electron beam lithography for nanophotonic device fabrication," J. Vac. Sci. Technol. B 33, 021603 (2015).

25) S. Fischbach, A. Schlehahn, A. Thoma, N. Sroka, T. Gissibl, S. Ristik, S. Thiele, A. Kaganasky, A. Strittmatter, T. Heindel, S. Rodt, A. Herkommer, H. Giessen, and S. Reitzenstein, "Single quantum dot with microlens and 3D-printed micro-objective as integrated bright single-photon source," ACS Photonics 4, 1327–1332 (2017).

26) P. Schnauber, J. Schall, S. Bounour, T. Hühne, S.-J. Park, G.-H. Rya, T. Heindel, S. Burger, J.-D. Song, S. Rodt, and S. Reitzenstein, "Deterministic integration of quantum dots into on-chip multimode interference beam splitters using in situ electron beam lithography," Nano Lett. 18, 2336–2342 (2018).

27) P. Schnauber, A. Singh, J. Schall, S. I. Park, J. D. Song, S. Rodt, K. Srinivasan, S. Reitzenstein, and M. Davanço, "Indistinguishable photons from deterministically integrated single quantum dots in heterogeneous GaAs/InP quantum photonic circuits," Nano Lett. 19, 7164–7172 (2019).

28) P. Reithmaier, G. Şapk, A. Löffler, C. Hofmann, S. Kuhn, S. Reitzenstein, L. V. Keldysh, V. D. Kulakovskii, T. L. Reinecke, and A. Forchel, "Strong coupling in a single quantum dot–semiconductor microcavity system," Nature 432, 197–200 (2004).

29) A. Thoma, P. Schnauber, M. Gschrey, M. Seifried, J. Wolters, J.-H. Schulze, A. Strittmatter, S. Rodt, A. Carmele, A. Knorr, T. Heindel, and S. Reitzenstein, "Exploring dephasing of a solid-state quantum emitter via time- and temperature-dependent Hong-Ou-Mandel experiments," Phys. Rev. Lett. 116, 033601 (2016).

30) S. Reitzenstein, S. Münch, P. Franke, A. Rahimi-Iman, A. Loﬄer, S. Höfling, L. Worschech, and A. Forchel, "Control of the strong light-matter interaction between an elongated InGaAs quantum dot and a microcavity using external magnetic fields," Phys. Rev. Lett. 103, 127401 (2009).

31) Y. H. Ye, Y.-M. He, Y.-J. Wei, X. Jiang, M.-C. Chen, F.-L. Xiong, Y. Zhao, C. Schneider, M. Kamp, S. Höfling, C.-Y. Lu, and J.-W. Pan, "Indistinguishable tunable single photons emitted by spin-ﬂip Raman transitions in InGaaS quantum dots," Phys. Rev. Lett. 111, 237403 (2013).

32) S. Seidl, M. Kroner, A. Kößle, K. Karrai, R. J. Warburton, A. Badolato, and P. M. Petroff, "Effect of uniaxial stress on excitons in a self-assembled quantum dot," Appl. Phys. Lett. 88, 203113 (2006).

33) F. Ding, R. Singh, J. D. Plumhof, T. Zander, V. Křápáek, Y. H. Chen, M. Benyoussef, V. Zwicker, K. Dörr, G. Bester, A. Rastelli, and O. G. Schmidt, "Tuning the exciton binding energies in single self-assembled InGaAs/GaAs quantum dots by piezoelectric-induced biaxial stress," Phys. Rev. Lett. 104, 067405 (2010).

34) R. Trotta, P. Atkinson, J. D. Plumhof, E. Zallo, R. O. Rezae, S. Kumar, S. Baunack, J. R. Schröter, A. Rastelli, and O. G. Schmidt, "Nanomembrane quantum-light-emitting diodes integrated onto piezoelectric actuators," Adv. Mater. 24, 2668–2672 (2012).

35) M. Schmid, V. M. Helversen, S. Fischbach, A. Kaganasky, R. Schmidt, A. Schliwa, T. Heindel, S. Rodt, and S. Reitzenstein, "Deterministically fabricated spectrally-tunable quantum dot based single-photon source," Opt. Mater. Express 10, 76 (2019).

36) A. W. Elshaar, E. Büyükköür, I. E. Zadeh, T. Lettner, P. Zhao, E. Schöll, S. Gyger, M. E. Reimer, D. Dalaca, D. Zobenica, L. H. Li, E. H. Linfield, and A. Fiore, "Quantum photonic integrated circuits based on quantum dots," Semicond. Sci. Technol. 34, 104041 (2019).

37) R. J. Warburton, C. Schulhauser, D. Haft, C. Schäferlin, K. Karrai, J. M. Garcia, W. Schoenfeld, and P. M. Petroff, "Giant permanent dipole moments of excitons in semiconductor nanostructures," Phys. Rev. B 85, 113303 (2002).

38) A. J. Bennett, R. B. Patel, J. Skiba-Szymanska, C. A. Nicoll, I. Farrer, D. A. Ritchie, and A. J. Shields, "Giant Stark effect in the emission of single semiconductor quantum dots," Appl. Phys. Lett. 97, 031104 (2010).

39) D. J. P. Ellis, A. J. Bennett, C. Dangel, J. P. Lee, I. P. Griffiths, T. A. Mitchell, T.-K. Paraíso, P. Spencer, D. A. Ritchie, and A. J. Shields, "Independent indistinguishability of quantum light sources on a reconfigurable photonic integrated circuit," Appl. Phys. Lett. 112, 211104 (2018).

40) D. T. F. Marples, "Refractive index of GaAs," J. Appl. Phys. 35, 1241–1242 (1964).

41) A. Schlehahn, S. Fischbach, R. Schmidt, A. Kaganasky, A. Strittmatter, S. Rodt, T. Heindel, and S. Reitzenstein, "A stand-alone fiber-coupled single-photon source," Sci. Rep. 8, 1340 (2018).

42) G. Kiršanské, H. Thyressrup, R. S. Daveau, C. L. Dreeßen, T. Pregolato, L. Baunack, J. R. Schröter, A. Rastelli, and O. G. Schmidt, "Controlled light-matter coupling in a planar nanobeam waveguide," Phys. Rev. B 96, 163306 (2017).

43) Z.-H. Xiang, J. Huwer, J. Skiba-Szymanska, R. M. Stevenson, D. J. P. Ellis, A. J. Farrer, M. B. Ward, D. A. Ritchie, and A. J. Shields, "A tuneable nanobeam wavelength entangled light emitting diode deployed in an installed fibre network," Commun. Phys. 3, 121 (2020).