A bright and fast source of coherent single photons

Natasha Tomm 1,3, Alisa Javadi 1,3 ✉, Nadia Olympia Antoniadis 4, Daniel Najer 1, Matthias Christian Löbl 1, Alexander Rolf Korsch 1,2, Rüdiger Schott 2, Sascha René Valentín 2, Andreas Dirk Wieck 2, Arne Ludwig 2 and Richard John Warburton 1

A single-photon source is an enabling technology in device-independent quantum communication 1, quantum simulation 2–5, and linear optics-based 6 and measurement-based quantum computing 7. These applications employ many photons and place stringent requirements on the efficiency of single-photon creation. The scaling on efficiency is typically an exponential function of the number of photons. Schemes taking full advantage of quantum superpositions also depend sensitively on the coherence of the photons, that is, their indistinguishability 8. Here, we report a single-photon source with a high end-to-end efficiency. We employ gated quantum dots in an open, tunable microcavity 9. The gating provides control of the charge and electrical tuning of the emission frequency; the high-quality material ensures low noise; and the tunability of the microcavity compensates for the lack of control in quantum dot position and emission frequency. Transmission through the top mirror is the dominant escape route for photons from the microcavity, and this output is well matched to a single-mode fibre. With this design, we can create a single photon at the output of the final optical fibre on-demand with a probability of up to 57% and with an average two-photon interference visibility of 97.5%. Coherence persists in trains of thousands of photons with single-photon creation at a repetition rate of 1 GHz.

A single emitter can be used as a single-photon source. Unlike a cold atom or ion in vacuum 10,11, a semiconductor quantum dot is naturally trapped in space. Photonic engineering on a nanoscale is required to funnel the photons into one specific mode and to couple the photons from this mode into a single-mode fibre 12. There are two established techniques. First, in a resonant microcavity, photons are emitted preferentially into the microcavity mode (the Purcell effect), and in an asymmetric microcavity, photon leakage from the microcavity acts as an out-coupler. Much success has been achieved with micropillars 12–14. Second, in an on-chip waveguide, photons are emitted preferentially into a laterally propagating mode 14,15. In terms of the end-to-end efficiency, a record of 24% has been achieved with a quantum dot in a micropillar 15.

Coherence depends sensitively on the noise in the device. Despite the complexity of the solid-state environment, quantum-dot-based single-photon sources have demonstrated close-to-unity coherence for the interference of successively emitted photons 11,13. Ultimately, the coherence is limited by exciton–phonon scattering, but with a careful choice of microcavity, two-photon interference visibilities as high as 99% are predicted 16. Experimentally, the coherence tends to drop on timescales of a few hundred nanoseconds, for instance from 96% to 92% (ref. 14). This is most likely a consequence of charge noise, which results in a fluctuating emission frequency. Charge noise can also result in telegraph noise should the charge state of the quantum dot itself fluctuate; this problem can be solved by working with a gated device in which the quantum dot charge is locked by a Coulomb blockade 17. An additional benefit of a gated device is that, within a charge plateau, the emission frequency can be fine-tuned electrically via the Stark effect. With resonant excitation on a gated device of very high material quality, the charge noise has been shown to be extremely low 18.

Here, we take the microcavity route to generating single photons from single quantum dots, employing a low-noise gated material. In the generic case (Jaynes–Cummings Hamiltonian with atom–cavity coupling g, cavity loss rate κ and atom decay rate into non-cavity modes Γ), β = F_0/(F_0 + 1) is the probability of photon emission into the cavity mode, where the Purcell factor is F_0 = 4g^2/κγ. Cavity loss channels are an exit through the top mirror (rate κ_top) and unwanted loss processes (rate κ_loss), such as absorption, scattering and diffraction to the side: κ = κ_top + κ_loss. The conversion efficiency of an exciton in the quantum dot to a photon exiting the top mirror of the cavity is η = β × κ_top/(κ + γ). For fixed g, γ and κ_loss, η exhibits a broad maximum around the condition κ_top = √((1 + κ_loss)/γ) × (4g^2 + κ_lossγ). Taking g ≫ κ_loss and g ≫ γ, the optimum value for κ_top is κ_opt ≈ 2g × √((1 + κ_loss)/γ). Taking a quantum dot with transform-limited linewidth (γ/(2π) = 0.3 GHz) in an open microcavity (g/(2π) = 4.3 GHz and κ_loss/(2π) = 0.72 GHz) 19, matching the condition on κ_top implies an efficiency η as high as 90% (Fig. 1b).

We use an open cavity 19,20 that is, a highly miniaturized Fabry–Perot cavity (Fig. 1a). The top mirror has a concave shape and is micro-machined into a silica substrate (Supplementary Information Section II); the bottom mirror is a highly reflective planar mirror, part of the semiconductor heterostructure 10 (Supplementary Information Section I). Quantum dots in this structure exhibit close-to-transform-limited linewidths (γ/(2π) = 0.30 GHz) 20. To determine the unwanted photon loss rate from the cavity, κ_loss we employ a highly reflective, extremely low-loss top mirror, keeping the mirror radius the same. With the same heterostructure and processing procedure, but with the highly reflective top mirror, we measure a high quality factor (Q-factor) at the stopband centre, Q = (4.5 ± 0.5) × 10^9 (Supplementary Information Section III and Supplementary Fig. 4). We obtain an upper bound to κ_loss/(2π) of (0.72 ± 0.07) GHz if we assume that only the unwanted losses determine the Q-factor. This low value of κ_loss arises on account of the low absorption rate and is only compatible with low diffraction losses (Supplementary Information Section V). We verify this point by calculating the Q-factor as a function of the mirror radius of curvature, r. These simulations, presented in Supplementary Fig. 6, show that diffraction...
losses reduce the $Q$-factor only for $r \leq 6 \mu m$. At the radius of curvature used here, $r = 12 \mu m$, the calculated $Q$-factor is 99% of the $Q$-factor in the large-$\tau$ limit. These simulations back up the experimental result that $\kappa_{\text{in}}$ is small. With the highly reflective top mirror, the quantum-dot/cavity system enters the strong coupling regime of cavity-quantum electrodynamics, allowing a precise measurement of the coupling, $g/(2\kappa) = 4.3 \text{GHz}$. In the simulations reported here, we use a modest reflectivity (transmission 30.300 ppm per round trip, according to the design) chosen such that $\kappa$ lies close to the efficiency maximum (Fig. 1b). The measured $Q$-factor is $12,600 \times 2 \pi = 25.92 \text{GHz}$, matching closely the value expected from the design of the two mirrors in the large-$\tau$ limit (Supplementary Information Section V). This analysis shows that $\kappa_{\text{in}}/(2\kappa) \approx 3\%$.

The semiconductor heterostructure contains thin n- and p-type layers with the quantum dots in tunnel contact with the n-type layer such that a Coulomb blockade is established (Supplementary Information Section I). Contacts to the n- and p-type layers are made at the edge of the chip, far from the microcavity itself. The chip is positioned relative to the top mirror in situ (Fig. 1a).

A challenge in all optically driven quantum dot single-photon sources is to separate the single-photon output from the driving laser light. A standard scheme is to excite and detect in a cross-polarized configuration. Applied to a charged exciton for which the transition is circularly polarized, this scheme leads to a 50% loss in the collection efficiency. Here, we avoid this loss by exploiting the linear birefringence arising mostly from some residual uniaxial strain in the semiconductor (Supplementary Information Section III); the spectrum of the laser pulses is larger than this splitting (Fig. 1c). The quantum dot is tuned into resonance with the higher-frequency, H-polarized mode. The laser is V-polarized and blue-detuned with respect to both microcavity modes such that the tails of the laser spectrum and the V-polarized microcavity mode overlap at the frequency of the H-polarized mode (Fig. 1c). The quantum dot emits preferentially into the H-polarized microcavity mode. The cross-polarization scheme (suppression 10$^6$ for pulsed excitation) now separates the V-polarized laser pulses from the H-polarized single photons with a loss depending only on the unwanted coupling of the quantum dot to the V-polarized mode (Supplementary Information Section V). Provided that the mode splitting is larger than the mode linewidths, this loss is small.

We choose a quantum dot and maximize the coupling of the X$^+$ resonance to the microcavity. To do this, we record a decay curve following resonant excitation: the radiative decay rate is largest at maximum coupling. The quantum dot and microcavity frequencies are tuned to establish a resonance (Fig. 2a). The Purcell factor $F_p$ is determined by scanning the microcavity frequency: on resonance with a microcavity mode, the decay time is 47.5 ps; far detuned, the decay time tends to 520 ps, resulting in $F_p = 10$ for quantum dot number one (QD1), and $F_p = 12$ for quantum dot six (QD6) (Fig. 2b). On resonance with the H-polarized microcavity mode, we determine $\beta_{\text{in}}$, the probability of emission into the H-polarized mode, to be $\beta_{\text{in}} = 86\%$ (Fig. 2b and Supplementary Information Section V).

We now maximize the flux of single photons. Implementing the excitation scheme (Fig. 1c), the central frequency of the laser is tuned to find the maximum signal. As a function of laser power, the quantum dot signal exhibits oscillations, indicative of Rabi oscillations

---

**Fig. 1 | Concept of the single-photon source. a.** The semiconductor heterostructure consists of a GaAs/AlAs Bragg mirror, the bottom mirror and a p-i-n diode. The InGaAs quantum dots (QDs) are located in the intrinsic region, in tunnel contact with the Fermi sea in the n layer. An electric voltage ($V_t$) is applied between the p and the n regions of the diode. The position of the heterostructure can be adjusted (+, -) with respect to the top mirror, a concave mirror in a silica substrate, using an xyz nano-positioner. A simulation (red points) shows that the output is very close to a Gaussian beam (black line, $\Delta \nu = 0.72 \text{GHz}$). The efficiency $(\text{η})$ is given by $\text{η} = \kappa_{\text{out}}/(2\kappa + \gamma) \approx 0.9995\%$. NA, numerical aperture.
The coherence of the single photons is probed with two-photon interference, a Hong–Ou–Mandel (HOM) experiment. On creating two photons 1 ns apart in time, the HOM visibility \( V_{\text{raw}} \) is 91.6\% (Fig. 3b). Correcting for a small imperfection in the HOM interferometer, \( V_{\text{raw}} = 92.5\% \). The HOM visibility is negatively influenced by fluctuation \( g^{(2)}(0) \) following the standard procedure, but the true photon overlap can be estimated to be \( V \approx (1 + 2g^{(2)}(0)) \times V_{\text{raw}} = 96.7\% \) (Supplementary Information Section IV). This demonstrates that successively generated photons are highly coherent. Crucial however is the coherence of photons separated much further apart in time. The HOM visibility on interfering two photons separated by 1.5\( \mu \)s in time is equally high (Fig. 3c). Given that photons can be created each with a nanosecond interval (Fig. 3b), these experiments demonstrate that the device can produce a string consisting of thousands of coherent photons. The dephasing time of the source is much larger than 1.5\( \mu \)s (Fig. 3d and Supplementary Information Section IV).

The noise in the single-photon flux is limited by shot noise on timescales of one hour (Fig. 4a), increasing only slightly on timescales of multiple hours (Fig. 4b). The tunability of the microcavity enables us to bring multiple quantum dots one-by-one into resonance with the same microcavity mode. Six quantum dots were investigated in detail. All six have similar values of end-to-end efficiency (Fig. 4c), coherence (Fig. 4d) and purity (Fig. 4e).

The \( \Sigma \) is a product of factors, \( \Sigma = P \times \beta_{\text{opt}} \times k_{\text{opt}} \times (\kappa + \gamma) \times \eta_{\text{optix}} \) where \( P \) is the probability of producing a photon on excitation with a laser pulse; and \( \eta_{\text{optix}} \) represents the throughput of the entire optical system (from microcavity to the output of the final output fibre). The \( \beta_{\text{opt}} \) and \( k_{\text{opt}} \) values are both determined in the experiment, and are \( (86 \pm 2)\% \) and \( (96 \pm 2)\% \), respectively. The \( \beta_{\text{opt}} \) value matches theoretical expectations based on the optical dipole moment and the microcavity geometry (Supplementary Information Section V). To determine \( P \), we describe the excitation scheme, a detuned laser pulse followed by ring-down, and how it drives a two-level system, including an intensity-dependent phonon-related dephasing process (Supplementary Information Section VIII). This calculation describes the Rabi oscillations (Fig. 2c), enabling us to infer that at the peak signal, \( P = (96.3 \pm 1.0)\% \). By building a replica of the optical set-up and measuring its throughput (Supplementary Information Section VI), we estimate \( \eta_{\text{optix}} = (69.0 \pm 3.6)\% \); \( \eta_{\text{optix}} \) is determined by losses on coupling the single photons into the single-mode fibre, and by reflection losses at three surfaces (upper surface of top mirror, two fibre facets) that lacked an antireflection coating.

The main new feature over previous experiments is the high end-to-end efficiency \( \Sigma \) of the source; \( \Sigma \) is neither the \( \beta \)-factor of the microcavity nor the efficiency after the first lens, both commonly used metrics. Instead, the end-to-end efficiency describes the efficiency of the entire chain: exciton creation, generation of a photon in the H-polarized microcavity mode, out-coupling of this photon through the top mirror and finally transmission through the entire optical system. In other words, following excitation with a laser pulse, we obtain a single photon at the output of the collection fibre (a standard optical fibre) with a probability \( \Sigma \). We determine \( \Sigma \) from the photon flux. At a repetition frequency of 76.3 MHz, we attenuate the beam by a factor of 9.9 (to avoid saturating the detector) and measure the count rate (Fig. 2c). Taking account of the detector efficiency and a small nonlinearity in the detector’s response (Supplementary Information Section VII), we determine \( \Sigma = (53 \pm 3)\% \) for QD1 (\( \Sigma = (57 \pm 3)\% \) for QD6), see Supplementary Information Section IX for measurement on QD6.
coating. This analysis predicts $\Sigma = (54.9 \pm 8.6)\%$, equal within error to the measured values, and suggests that the main contribution to the overall losses lies in $\eta_{\text{optics}}$.

We point out that, first, based on our analysis, a single-photon source with an end-to-end efficiency of 80% is within reach by eliminating the losses in the optical components. Second, the mode splitting can be tuned to increase $\beta_H$. The mode splitting can be controlled with the electro-optic effect\textsuperscript{23} or by deliberately introducing birefringence to the top mirror\textsuperscript{24}. Third, even better performance is conceivable by increasing the coupling via miniaturization of the top mirror and decreasing the bare decay rate via lateral structuring. Fourth, a more compact and stiffer device will be less susceptible to external noise, and a monolithic device is conceivable by relying on strain tuning to bring a quantum dot into resonance with a fixed-frequency microcavity mode\textsuperscript{25}. Finally, in addition to the applications as a single-photon source, a further broad area of application exploits the spin of the trapped hole. Implementing spin manipulation in the microcavity device, for instance by driving Raman transitions via lateral excitation\textsuperscript{26}, may facilitate applications such as a single-photon transistor\textsuperscript{27}, the efficient and fast creation of spin–photon entangled pairs and an efficient source of multi-photon cluster states\textsuperscript{28}.

**Online content**

Any methods, additional references, Nature Research reporting summaries, source data, extended data, supplementary information,
acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41565-020-00831-x.

Received: 7 August 2020; Accepted: 30 November 2020; Published online: 28 January 2021

References

1. Barrett, J., Hardy, L. & Kent, A. No signaling and quantum key distribution. Phys. Rev. Lett. 95, 010503 (2005).
2. Aaronson, S. & Arkhipov, A. The computational complexity of linear optics. In Proc. Forty-Third Annual ACM Symposium on Theory of Computing 333–243 (2011).
3. Wang, H. et al. Boson sampling with 20 input photons and a 60-mode interferometer in a 10^{14}-dimensional Hilbert space. Phys. Rev. Lett. 123, 250503 (2019).
4. Wang, J., Sciarrino, F., Laing, A. & Thompson, M. G. Integrated photonic quantum technologies. Nat. Photon. 14, 273–284 (2020).
5. Raussendorf, R. & Harrington, J. Fault-tolerant quantum computation with high threshold in two dimensions. Phys. Rev. Lett. 98, 190504 (2007).
6. Sangouard, N. & Zbinden, H. What are single photons good for? J. Mod. Opt. 59, 1458–1464 (2012).
7. Najer, D. et al. A gated quantum dot strongly coupled to an optical microcavity. Nature 575, 622–627 (2019).
8. McKeever, J. et al. Deterministic generation of single photons from one atom trapped in a cavity. Science 303, 1992–1994 (2004).
9. Meraner, M. et al. Indistinguishable photons from a trapped-ion quantum network node. Phys. Rev. A 102, 052614 (2020).
10. Lodahl, P., Mahmoodian, S. & Stobbe, S. Interfacing single photons and single quantum dots with photonic nanostructures. Rev. Mod. Phys. 87, 347–400 (2015).
11. Somaschi, N. et al. Near-optimal single-photon sources in the solid state. Nat. Photon. 10, 340–345 (2016).
12. Wang, H. et al. Near-transform-limited single photons from an efficient solid-state quantum emitter. Phys. Rev. Lett. 116, 213601 (2016).
13. Wang, H. et al. Towards optimal single-photon sources from polarized microcavities. Nat. Photon. 13, 779–775 (2019).
14. Arcari, M. et al. Near-unity coupling efficiency of a quantum emitter to a photonic crystal waveguide. Phys. Rev. Lett. 113, 093603 (2014).
15. Üpä, R. et al. Scalable integrated single-photon source. Sci. Adv. 6, eabk2668 (2020).
16. Iles-Smith, I., McCutcheon, D. P. S., Nazir, A. & Mork, J. Phonon scattering inhibits simultaneous near-unity efficiency and indistinguishability in semiconductor single-photon sources. Nat. Photon. 11, 521–526 (2017).
17. Warburton, R. J. et al. Optical emission from a charge-tunable quantum ring. Nature 405, 926–929 (2000).
18. Kuhlmann, A. V. et al. Charge noise and spin noise in a semiconductor quantum device. Nat. Phys. 9, 570–575 (2013).
19. Barbour, R. J. et al. A tunable microcavity. J. Appl. Phys. 110, 053107 (2011).
20. Wang, D. et al. Turning a molecule into a coherent two-level quantum system. Nat. Phys. 15, 483–489 (2019).
21. Santori, C., Fattal, D., Vuckovic, I., Solomon, G. & Yamamoto, Y. Indistinguishable photons from a single-photon device. Nature 419, 594–597 (2002).
22. Ramsay, A. J. et al. Damping of exciton Rabi rotations by acoustic phonons in optically excited InGaAs/GaAs quantum dots. Phys. Rev. Lett. 104, 017402 (2010).
23. Frey, J. A. et al. Electro-optic polarization tuning of microcavities with a single quantum dot. Opt. Lett. 43, 4280–4283 (2018).
24. Uphoff, M., Brekenfeld, M., Rempe, G. & Ritter, S. Frequency splitting of polarization eigenmodes in microscopic Fabry–Perot cavities. New J. Phys. 17, 013053 (2015).
25. Seidl, S. et al. Effect of uniaxial stress on excitons in a self-assembled quantum dot. Appl. Phys. Lett. 88, 203113 (2006).
26. Muller, A. et al. Resonance fluorescence from a coherently driven semiconductor quantum dot in a cavity. Phys. Rev. Lett. 99, 187402 (2007).
27. Chang, D. E., Sorensen, A. S., Demler, E. A. & Lukin, M. D. A single-photon transistor using nanoscale surface plasmons. Nat. Phys. 3, 807–812 (2007).
28. Schwartz, I. et al. Deterministic generation of a cluster state of entangled photons. Science 354, 434–437 (2016).

Publisher’s note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.
© The Author(s), under exclusive licence to Springer Nature Limited 2021
Data availability
The data that is presented in the main text can be downloaded from https://doi.org/10.5281/zenodo.4392853. The data will be available after an embargo period of six months, which starts from the final publication date of the manuscript.

Code availability
The code that has been used for this work is available from the corresponding author upon reasonable request.

Acknowledgements
We thank A. Brash, P. Lodahl, N. Sangouard and S. Starosielec for fruitful discussions. We acknowledge financial support from Swiss National Science Foundation project 200020_175748, NCCR QST and Horizon-2020 FET-Open Project QLUSTER. A.J. acknowledges support from the European Unions Horizon 2020 Research and Innovation Programme under Marie Skłodowska-Curie grant agreement no. 840453 (HiFig). S.R.V., R.S., A.L. and A.D.W. gratefully acknowledge support from DFH/UFU CDPA05-06, DFG TRR160, DFG project 383065199 and BMBF QLink.X.

Author contributions
N.T., A.J., N.O.A. and D.N. carried out the microcavity experiments. M.C.L. characterized the quantum dots and optimized the photon counting hardware. N.T. and D.N. fabricated the curved mirror. D.N., A.L. and R.J.W. designed the heterostructure. D.N. developed the surface passivation technique. A.R.K., R.S., S.R.V., A.D.W. and A.L. fabricated the semiconductor device. A.J. developed the model of the excitation mechanism. D.N. carried out the numerical simulations of the microcavity mode. N.T., A.J. and R.J.W. wrote the paper with input from all authors.

Competing interests
The authors declare no competing interests.

Additional information
Supplementary information is available for this paper at https://doi.org/10.1038/s41565-020-00831-x.

Correspondence and requests for materials should be addressed to A.J.

Peer review information Nature Nanotechnology thanks the anonymous reviewers for their contribution to the peer review of this work.

Reprints and permissions information is available at www.nature.com/reprints.