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An electrically driven cavity-enhanced source of indistinguishable photons with 61% overall efficiency

A. Schlehahn,[1] A. Thoma,[1] P. Munnelly,[1] M. Kamp,[2] S. Höfling,[2,3]
T. Heindel,[1,a] C. Schneider,[2] and S. Reitzenstein[1]
[1]*Institut für Festkörperphysik, Technische Universität Berlin, 10623 Berlin, Germany*
[2]*Technische Physik, Physikalisches Institut, Wilhelm Conrad Röntgen Research Center for Complex Material Systems, Universität Würzburg, 97074 Würzburg, Germany*
[3]*SUPA, School of Physics and Astronomy, University of St. Andrews, St. Andrews KY16 9SS, United Kingdom*

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We report on an electrically driven efficient source of indistinguishable photons operated at pulse-repetition rates f up to 1.2 GHz. The quantum light source is based on a p-i-n-doped micropillar cavity with integrated self-organized quantum dots, which exploits cavity quantum electrodynamics effects in the weak coupling regime to enhance the emission of a single quantum emitter coupled to the cavity mode. We achieve an overall single-photon extraction efficiency of (61 ± 11) % for a device triggered electrically at $f = 625$ MHz. Analyzing the suppression of multi-photon emission events as a function of excitation repetition rate, we observe single-photon emission associated with $g^{(2)}_{HBT}(0)$ values between 0.076 and 0.227 for f ranging from 373 MHz to 1.2 GHz. Hong-Ou-Mandel-type two-photon interference experiments under pulsed current injection at 487 MHz reveal a photon-indistinguishability of (41.1 ± 9.5) % at a single-photon emission rate of (92 ± 23) MHz. [http://dx.doi.org/10.1063/1.4939831]

Semiconductor quantum dots (QDs) are excellent candidates for the realization of practical quantum light sources[1] for future applications in quantum information technology,[2] due to the ease of integration into complex micro- and nanophotonic structures and their superior quantum optical properties. In particular, the realization of electrically operated QD-based non-classical light sources is a very active field,[3] exhibiting milestones such as the first demonstration of an electrically driven source of single photons[4] or entangled photon pairs[5] as well as quantum key distribution experiments.[6] On the other hand, while high photon-indistinguishabilities have been achieved in numerous Hong-Ou-Mandel (HOM)-type two-photon interference (TPI) experiments under optical pumping using quasi-resonant[7,8] or strict-resonant[9,10] excitation schemes, the generation of indistinguishable photons via electrically driven QD devices remains very challenging, due to the intrinsic above-band injection of charge-carriers resulting in an inherent relaxation time jitter as well as dephasing due to electric field noise.[11] Bennett *et al.*[12] demonstrated the electrical generation of indistinguishable photons emitted by a QD, by exploiting the quantum-confined Stark-effect to tune the QD emission in and out of the spectral detection window on a time scale short compared to the radiative lifetime of the QD transition. However, this scheme inherently leads to a reduced quantum efficiency of the QD, which limits the single-photon emission rate. In contrast, exploiting the Purcell-effect[13] in microcavity structures conceptually allows for the generation of photons with short radiative lifetimes at high photon extraction efficiencies under electrical excitation.[14,15]

[a]Author to whom correspondence should be addressed. Electronic mail: tobias.heindel@tu-berlin.de

In this work, we realize an efficient, electrically triggered source of indistinguishable single photons. Exploiting the Purcell-effect in electrically contacted QD micropillar cavities operated at excitation repetition rates up to 1.2 GHz, we extract the cavity-enhanced single-photon emission with record-high total efficiencies up to (61 ± 11) %. Moreover, TPI experiments under pulsed current injection at 487 MHz reveal a photon-indistinguishability of (41.1 ± 9.5) % at a single-photon emission rate of (92 ± 23) MHz.

The single-photon source (SPS) used in our experiments is composed of a low-density layer of self-organized InAs QDs embedded in an intrinsic λ-thick GaAs-cavity. An n-type δ-doped layer is introduced close to the QDs to eliminate detrimental dark-state configurations.[16] The cavity is sandwiched between a lower n-doped and an upper p-doped distributed Bragg reflector (DBR) containing 26 and 13 AlAs/GaAs mirror pairs, respectively. The mirror number was optimized for the highest photon extraction efficiencies resulting in moderate Q factors (~1300 to 2300) for devices of 2.0 μm diameter.[15] Electrically contacted micropillars are processed via electron beam lithography and reactive ion etching[17] to realize the final device illustrated in Fig. 1(a).

The sample is operated in a liquid-helium-flow cryostat at temperatures from 4 K to 30 K. To electrically excite the QD micropillar with high pulse-repetition rates, we use a pulse pattern generator (HP 8133A) with a minimal pulse-width of 50 ps and a maximal repetition rate of 3 GHz. Electrical voltage pulses are applied to the sample via the cryostats' high-frequency capable feedthroughs and a probe needle. A microscope objective (numerical aperture: 0.4), serving as first lens of the detection system, collects and collimates the electroluminescence of the QD-micropillar chip. The collimated emission is spectrally analyzed using a spectrometer enabling a spectral resolution of 25 μeV. The photon statistics of the sample emission is analyzed by means of photon-autocorrelation measurements in a Hanbury-Brown and Twiss (HBT) setup. To investigate the photon-indistinguishability, HOM-type TPI experiments were performed via an asymmetric Mach-Zehnder interferometer based on polarization-maintaining single-mode fibers. Both the HBT and HOM setup utilize two silicon-based single photon counting modules (SPCMs) and time-correlated single-photon counting (TCSPC) electronics for coincidence measurements (see Ref. 8 for details).

For the experiments, a QD micropillar with a diameter of 2.0 μm has been chosen to achieve optimum photon extraction efficiency. Prior to the quantum optical studies, spectral resonance between a single quantum emitter and the cavity mode was induced via temperature tuning. Fig. 1(b) shows micro-electroluminescence (μEL) spectra of a QD micropillar as a function of sample temperature in a contour plot. The device was operated under pulsed electrical current injection at a repetition rate of 373 MHz (pulse-width: 200 ps, DC bias: 1.49 V, pulse-amplitude: 1.38 V). At

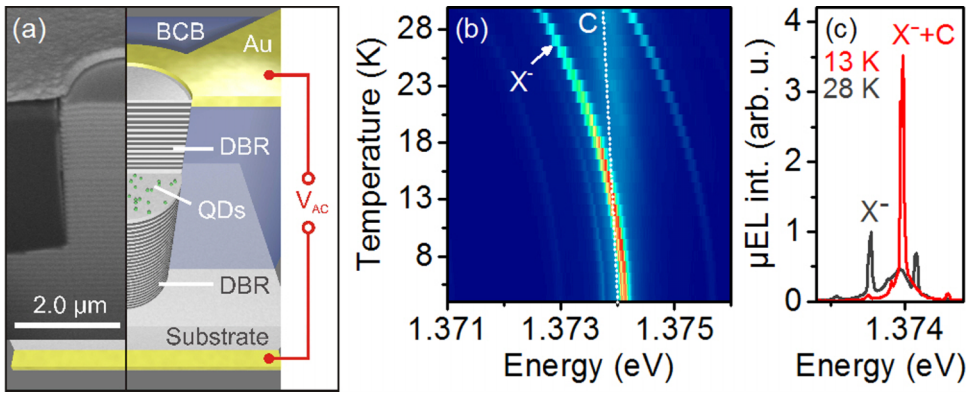

FIG. 1. (a) Illustration of the indistinguishable-photon emitting diode based on a quantum dot (QD) micropillar cavity structure. A cross-sectional scanning electron microscopy image of a fully processed device (left panel) as well as a schematic (right panel) is shown. (b) Contour plot of emission spectra of a QD micropillar vs. sample temperature. The device was operated under pulsed electrical current injection at a repetition rate of 373 MHz. Pronounced Purcell enhancement of the emission is observed by tuning a single QD exciton (X^-) in spectral resonance with the cavity mode (C). (c) μEL spectra of the X^- emission on- (13 K) and off- (28 K) resonance with the cavity mode C.

a temperature of 28 K, the emission of a singly negatively charged exciton state X^- is observed at the low energy side of the cavity mode C ($Q = 2100 \pm 100$). Decreasing the temperature results in a spectral shift of the X^- emission towards the cavity mode at higher energies, accompanied by a pronounced increase of the emission intensity due to the Purcell-effect. The maximum Purcell-induced emission enhancement is reached at spectral resonance with the cavity mode at a temperature of 13 K. We have deliberately chosen a QD resonance at rather low temperatures, as phonon-induced pure dephasing is known to severely affect the photon-indistinguishability.[18,19] To determine the Purcell-factor F_P from the μEL spectra, we extracted the integrated emission intensity of the X^- state as a function of the spectral detuning to the cavity mode and applied formula (10) from Ref. 20, yielding $F_P = 3.2 \pm 0.4$.

To gain insight into the photon statistics of the QD emission, we performed measurements of the second-order photon-autocorrelation $g^{(2)}(\tau)$. For this purpose, the spectrally filtered emission of the resonantly coupled X^- state (cf. Fig. 1(c)) was coupled to the HBT setup. The resulting coincidence histogram of $g^{(2)}_{HBT}(\tau)$ is presented in the upper panel of Fig. 2(a). Electrically triggered single-photon emission of the coupled QD-cavity system is reflected in the strongly reduced number of coincidences at zero time delay ($\tau = 0$). At finite τ, coincidence maxima occur at a periodicity, corresponding to the pulse-repetition rate of 373 MHz. For a quantitative evaluation of the suppression of two-photon emission events, we fitted the experimental data with a sequence of equidistant photon pulses, each represented by the convolution of a two-sided exponential (decay-time-constant τ_D) with a Gaussian of 350 ps width (full-width at half-maximum), accounting for the HBT's timing resolution. Assuming a constant area A of the pulses at finite time delay, $g^{(2)}_{HBT}(0)$ is expressed by the ratio A_0/A, where A_0 corresponds to the area of the zero-delay peak. The fitted model function (red line in Fig. 2(a)) reveals an antibunching of $g^{(2)}_{HBT}(0) = 0.076 \pm 0.014$, demonstrating triggered single-photon emission with excellent suppression of multi-photon emission events. The combined detection rate of the SPCMs amounts to 240 kHz. Taking the detection efficiency of the HBT setup $\eta_{HBT} = (2.45 \pm 0.29) \times 10^{-3}$ (measured according to Ref. 21), we are able to deduce

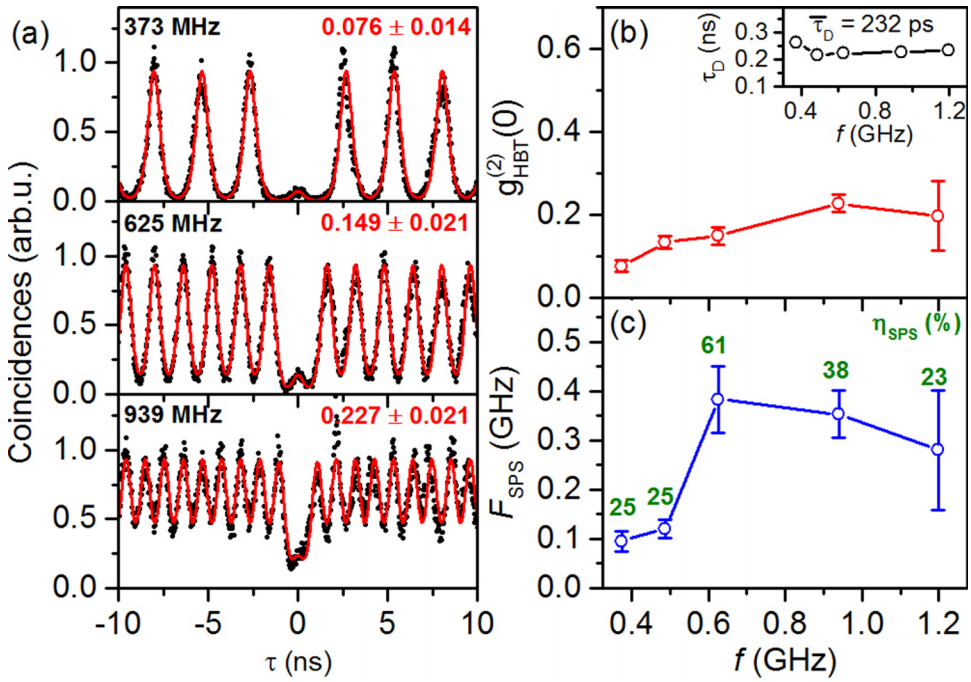

FIG. 2. Photon-autocorrelation analysis (HBT configuration) of an electrically triggered coupled QD-cavity device. (a) Exemplary coincidence histograms for increasing excitation repetition rate f. Red lines represent a fit to the data assuming a mono-exponential radiative decay and considering the timing resolution of the detection system. Extracted $g^{(2)}_{HBT}(0)$ values (highlighted in red) are depicted in (b) as a function of f. Inset: extracted decay time τ_D of the QD transition. (c) Single photon emission rate F_{SPS} and the corresponding overall efficiency η_{SPS} vs. f.

the photon flux F emitted into the first lens of the setup to $F = 240$ kHz/$\eta_{HBT} = (99 \pm 11)$ MHz. Correcting for two-photon emission events according to Ref. 22, we obtain the single-photon emission rate $F_{SPS} = F \times (1 - g^{(2)}_{HBT}(0))^{1/2} = (95 \pm 20)$ MHz, which corresponds to an overall efficiency of the SPS of $\eta_{SPS} = F_{SPS}/f = (25.4 \pm 5.5)$ %. To evaluate the performance of our device at the highest modulation frequencies, we gradually increased the excitation repetition rate. Here, DC bias and pulse-amplitude have been adjusted slightly for each excitation repetition rate ($\lesssim$10% change of the above mentioned parameters), in order to optimize the signal-to-background ratio. The middle and lower panels of Fig. 2(a) exemplarily depict HBT measurements at modulation speeds of 625 MHz and 939 MHz together with a fit to the experimental data. Both histograms reveal strong antibunching and clearly attest single-photon emission of the QD-cavity system at ultra-high repetition rates. As seen from Fig. 2(b), where the extracted $g^{(2)}_{HBT}(0)$ values are presented as a function of modulation speed, the suppression of two-photon emission events remains well below 0.25 in the entire frequency range. Only a slight increase in $g^{(2)}_{HBT}(0)$ is observed, which most probably results from increased contributions of uncorrelated background emitters non-resonantly feeding the cavity mode[23–25] due to an f-dependent current density distribution within the QD-layer (cf. discussion of Fig. 2(c)). While at 625 MHz the coincidence maxima still remain well separated in time, they show a significant overlap at 939 MHz, as the modulation speed gets comparable to the inverse decay time of the QD state ($1/\tau_D = 4.3$ GHz). Here, the QD decay time τ_D of (232 ± 18) ps has been extracted from the fit to the HBT measurements and is found to be almost constant over the investigated frequency range, as expected. Fig. 2(c) displays the deduced single-photon emission rate F_{SPS} into the first lens as a function of modulation speed f. The maximal rate of $F_{SPS} = (383 \pm 68)$ MHz is achieved at a modulation speed of 625 MHz, associated with a combined detected rate at the SPCMs of 1 MHz. The associated overall efficiency of $\eta_{SPS} = F_{SPS}/f = (61 \pm 11)$ % is the highest efficiency reported for electrically triggered SPSs so far and represents a significant improvement compared to our previous work of Ref. 15. Further increasing the modulation speed f to 939 MHz, F_{SPS} and η_{SPS} first stagnate and finally at 1.2 GHz slightly decrease. Interestingly, the highest measured overall efficiency of (61 ± 11) % compares well with the estimated photon extraction efficiency[26] of $\eta_{ext} = Q/Q_{2D} \times F_P/(F_P + 1) = 53\%$ of the present device, with experimentally determined values for Q and F_P from above and $Q_{2D} = 3000$,[15] indicating that the electrical injection efficiency into the QD is very high. The observation of a frequency-dependent overall efficiency η_{SPS} further suggests an f-dependent current injection efficiency into the QD. A possible explanation for this effect, which is typically observed for this type of structure,[27] is a frequency-dependent spatial current density distribution within the QD layer. The same effect possibly also causes the f-dependence of $g^{(2)}_{HBT}(0)$ (cf. Fig. 2(b)), which reduces the efficiency at high repetition rates due to the correction for two-photon emission events.

Next, the photon-indistinguishability is addressed by TPI experiments. For this purpose, the cavity-enhanced X^- emission electrically triggered at 487 MHz is coupled to the HOM setup, where the repetition rate has been chosen to coarsely match the delay in the interferometer while a fine adjustment was performed via a variable fiber-delay. Fig. 3(a) displays the obtained coincidence histogram of the two-photon detection events at the two outputs of the HOM interferometer for

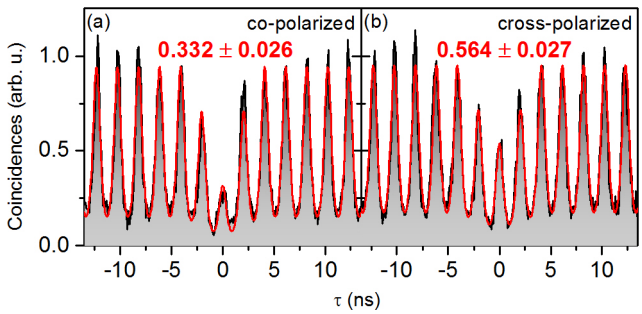

FIG. 3. Hong-Ou-Mandel-type two-photon interference (TPI) experiment on the single-photon stream emitted by our device at a repetition rate of 487 MHz. Experimental data for co-polarized (a) and cross-polarized (b) measurement configuration are presented as well as the corresponding fits (red lines), revealing a TPI visibility of 41%.

co-polarized measurement configuration. Quantum-mechanical TPI manifests in a strongly reduced number of coincidences at $\tau = 0$, if compared to the measurement in cross-polarized configuration (cf. Fig. 3(b)). To quantitatively extract the visibility of TPI, i.e., the mean photon wave-packet overlap, we fitted the experimental data according to the model applied in Fig. 2(a). Additionally, the peak areas at $\tau = \pm 2.062$ ns have been fixed to the theoretically expected value of $0.75A$, where A corresponds to the area of the peaks at $|\tau| > 2.062$ ns in this case.[12] The peak area ratio of $3/4$ can thereby be deduced by combinatorics, assuming an asymmetric Mach-Zehnder interferometer with 50:50 beam-splitters and calculating the possible pulse-configurations leading to coincidences at finite τ. From the extracted relative peak areas A_0/A, we gain values of $g^{(2)}_{\parallel}(0) = 0.332 \pm 0.026$ and $g^{(2)}_{\perp}(0) = 0.564 \pm 0.027$ for the antibunching in co- and cross-polarized measurement configurations, respectively. The corresponding visibility of two-photon interference yields $V = (g^{(2)}_{\perp}(0) - g^{(2)}_{\parallel}(0))/g^{(2)}_{\perp}(0) = (41.1 \pm 9.5)$ %. The X^- state showed a combined detection rate at the SPCMs of the HOM setup of $R_{\mathrm{det}} = (25.5 \pm 1.5)$ kHz, which corresponds to a flux $F_{\mathrm{ISPS}} = R_{\mathrm{det}} \times (1 - g^{(2)}_{\mathrm{HBT}}(0))^{1/2}/\eta_{\mathrm{HOM}} = (92 \pm 23)$ MHz of single photons with 41% TPI visibility. Here, we corrected F_{ISPS} for multi-photon emission events present in the actual HOM experiment by independently measuring $g^{(2)}_{\mathrm{HBT}}(0) = 0.139 \pm 0.030$ and took into account the detection efficiency of the HOM setup ($\eta_{\mathrm{HOM}} = (0.258 \pm 0.030) \times 10^{-3}$). The corresponding overall efficiency is (18.8 ± 4.6) % and equals the product of the charge-carrier injection efficiency and the estimated photon extraction efficiency ($\eta_{\mathrm{ext}} \sim 53\%$, see above), where η_{ext} depends only on the cavity parameters and the Purcell factor. Thus, we estimate a charge-carrier injection efficiency of $\sim$35% ($=\eta/\eta_{\mathrm{ext}}$) which limits the efficiency at this specific working point. Although the TPI visibility of (41.1 ± 9.5) % observed in our experiment is quite remarkable for non-resonant excitation schemes,[28] it is still significantly lower compared to experiments using quasi- or strict-resonant optical excitation, where visibilities close to unity have been reported.[7,10,29,19] A possible reason is the finite time jitter resulting from the phonon-mediated relaxation of charge carriers from the bulk material into the QDs, leading to a jitter in the arrival time at the HOM beam splitter thus reducing the photon wave-packet overlap. This time jitter can be reduced, by exploiting advanced above band electrical excitation schemes[12,30] at the cost of lower device efficiencies. Additionally, dephasing due to electric field noise generated by fluctuating charge traps reduces the degree of TPI.[11] Thus, we conclude that resonant electrical injection schemes[31–33] or on-chip optical excitation schemes[34] might be useful to simultaneously achieve high photon-indistinguishabilities and high efficiencies in an integrated device approach.

In summary, we realized an ultra-bright electrically triggered source of indistinguishable photons based on a QD micropillar cavity operated at a modulation speed of up to 1.2 GHz. Due to the pronounced Purcell-effect, we achieve an overall efficiency of (61 ± 11) % at 625 MHz. Additionally, HOM-type TPI experiments under pulsed current injection at 487 MHz reveal a photon-indistinguishability of (41.1 ± 9.5) % at a single-photon emission rate of (92 ± 23) MHz. The presented results are promising with respect to the realization of practical and highly integrated quantum light sources for applications in quantum information technology.

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