Highly efficient electrically triggered quantum dot micropillar single photon source

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Abstract. We present electrically triggered single photon emission from low mode volume quantum dot-micropillar cavities at operating frequencies of up to 220 MHz. Due to an optimized layout of the doped planar microcavity and an advanced lateral current injection scheme, highly efficient single photon sources featuring $g^{(2)}(0)$-values well below 0.5 and a Purcell factor of 4 are realized. Single photon emission at a rate as high as $(47.0 \pm 6.9)$ MHz with a corresponding overall efficiency of $(21.4 \pm 3.1)\%$ is demonstrated for a $2.0 \mu m$-diameter device.

1. Introduction
Motivated by possible applications in quantum communication systems great efforts have been made in recent years with respect to the realization of efficient single photon sources (SPSSs). Due to their discrete energy levels single quantum dots (QDs) can inherently act as single photon emitters and are therefore predestined for solid state SPSs. However, QDs suffer from a poor outcoupling efficiency when embedded in a bulk semiconductor matrix since most of the isotropically emitted photons are trapped due to total internal reflection. The efficiency of a QD based SPS is strongly enhanced in combination with high quality microcavities [1, 2]. In this respect QD-micropillar cavities are very attractive systems due to a high extraction efficiency approaching 70%, as predicted by theory [3], and a highly directional emission normal to the sample surface. Moreover, in light of possible applications of SPSs, e.g. in quantum key distribution systems, and the associated device integration it is crucial to establish an electrical pumping scheme capable for high frequency operation. Up to now only a few approaches for electrically pumped SPS based on QDs embedded in oxide apertured pin-diodes with and without cavity effects and an efficiency of up to 14% have been demonstrated [4]. In this work we will demonstrate highly efficient single photon emission (SPE) from an electrically triggered QD-micropillar cavity as depicted schematically in Fig. 1. We observe overall efficiencies of up to 21% and record high SPE rates as high as 47 MHz, the latter even outperforms values reported in [5].
2. Sample structure and measurement setup
The electrically contacted micropillar SPSs are based on a planar GaAs/AlAs microcavity sample with a n-doped lower and a p-doped upper distributed Bragg reflector (DBR) grown by molecular beam epitaxy on a n-doped GaAs substrate. The one-λ thick undoped GaAs cavity, which is embedded between the DBRs, contains a low density layer of InAs QDs. In the vicinity of the latter we introduced a n-type δ-doped layer to eliminate dark-state configurations that are known to reduce the efficiency of SPSs based on neutral QDs [2]. The asymmetric layout of the planar microcavity with 13 (26) AlAs/GaAs mirror pairs in the upper (lower) DBR was designed for highest outcoupling efficiencies using three-dimensional finite difference time-domain simulations. This optimization results in a moderate Q-factor of the planar cavity of about 3000. The lateral mode confinement is obtained by patterning pillars with a circular cross section with diameters $d_C$ of 1-4 µm. The small number of mirror pairs in the upper DBR ensures a strongly directional emission normal to the sample surface so that photon losses due to sidewall imperfections of the micropillars are of minor importance. We refer to [6] for a more detailed discussion of the different loss channels. Furthermore, in our approach, the uncovered top facet of the micropillar guarantees efficient in- and outcoupling of light [7].

The device was investigated by means of high-resolution micro-electroluminescence (µEL) spectroscopy at low temperatures (10-70 K). Single photon emission was probed using a fiber coupled Hanbury-Brown and Twiss (HBT) setup with Si-based avalanche photon diodes (APDs) acting as detectors. The overall temporal resolution of the HBT setup is approximately 0.7 ns. Moreover, time resolved µEL-measurements were performed with a fast Si-APD enabling a temporal resolution of 40 ps. The SPS was triggered by an electrical pulse generator providing pulses with widths down to 200 ps (FWHM) at a repetition rate of up to 250 MHz. In addition, a DC offset could be applied to the sample.

3. Experimental results and discussion
In the following we present highly efficient, electrically triggered single photon emission of a micropillar with a diameter of $d_C=2$ µm.

![Figure 2](image_url)

**Figure 2.** (a) µEL-spectra of a 2 µm diameter micropillar under pulsed excitation at 220 MHz ($V_{DC}=1.65$ V). Resonance of the cavity mode C and a single QD exciton $X^-$ is observed at 31.5 K, where the intensity of the excitonic-line is strongly enhanced due to the Purcell effect. (b) Time resolved µEL-signal recorded for the resonance-condition in (a). (c) Photon autocorrelation measurement under on-resonance condition at $V_{DC}=1.85$ V.
3.1. Cavity enhanced single photon emission

Fig. 2(a) displays $\mu$EL-spectra of the micropillar for two different temperatures under pulsed excitation at 220 MHz. The device was biased with a DC voltage $V_{DC}$ of 1.65 V, just below the onset of EL. In addition, pulses with an amplitude $V_{AC}$ of 6.0 V were applied. At 23.8 K, a single QD exciton ($X^-$) as well as the very weak fundamental cavity mode (C) with a Q-factor of 2300 can be identified. The charged state of the exciton was thereby confirmed by polarization dependent measurements.

By increasing the sample temperature to 31.5 K, the $X^-$-line can be tuned on resonance with the cavity mode, which results in a strong enhancement of emission due to the Purcell effect [7].

The suitability of our devices with respect to the injection of short electrical pulses is demonstrated in Fig. 2(b) which shows time resolved $\mu$EL emitted at resonance (31.5 K). In fact, we observe a train of well shaped narrow pulses at a repetition rate of 220 MHz which allows us to estimate the Purcell factor for the resonant QD. The EL decay yields a recombination lifetime $\tau_{QD, res} = (296\pm8) \text{ps}$ of the resonant QD as illustrated in Fig. 2(b). The bulk QD lifetime $\tau_{QD, bulk} = (1.20\pm0.05) \text{ns}$ was independently obtained by ensemble measurements on another sample from the same wafer whose top DBR was removed by plasma etching. From these numbers, we determine a Purcell factor of $F_P = 4.0\pm0.2$ which is close to the maximal achievable value of $F_P = 3Q/(4\pi^2V_{eff})(\lambda/n)^3 = 5$ for the present QD-micropillar system under spatial and spectral resonance [7]. It is worth mentioning that the fast response of the SPS should allow for repetition rates in the GHz range as reported in [8].

To test the emission of this resonantly coupled QD-cavity system with respect to its photon statistics, the $\mu$EL-signal was coupled to the HBT-setup. The corresponding photon autocorrelation function $g^{(2)}(\tau)$ was measured for $V_{DC} = 1.85 \text{ V}$ ($V_{AC} = 6 \text{ V}$, $f = 220 \text{ MHz}$) and is depicted in Fig. 2(c). Non-classical emission of light is identified by the strongly reduced peak at $\tau=0$ and the measured $g^{(2)}(0)$-value of $(0.30\pm0.03)<0.5$, which is an unambiguous proof of single photon emission from the QD-micropillar device. The deviation from the ideal value of $g^{(2)}(0)=0$ can be partly explained by taking uncorrelated background emissions from the cavity mode into account [9]. Further negative influence on $g^{(2)}(0)$ might be related to recapture processes and the associated multi-photon emission events.

3.2. Estimating the single photon emission rate

In order to evaluate the performance of the micropillar SPS in terms of the overall efficiency, i.e. the probability of emitting a single photon after an electrical input pulse, as well as the SPE rate under pulsed electrically current injection, we carefully calibrated our experimental HBT-setup to determine the photon emission rate $\dot{n}$. This detection rate needs to be corrected for multi photon emission events to obtain an estimate for the true SPE rate $\dot{n}_{SPE} = \dot{n}\sqrt{1 - g^{(2)}(0)}$ [10].

Fig. 3 displays $\dot{n}_{SPE}$ and the corresponding $g^{(2)}(0)$-values as a function of $V_{DC}$ ($V_{AC} = 6 \text{ V}$ and $f = 220 \text{ MHz}$). Here, the DC bias allows for a precise adjustment of carrier capture rate into the QDs. At $V_{DC} = 1.85 \text{ V}$ we obtain a SPE rate of $\dot{n}_{SPE} = 20.5 \text{ MHz}$. The latter increases up to $\dot{n}_{SPE} = 47.9 \text{ MHz}$ at $V_{DC} = 2.10 \text{ V}$ accompanied by successive saturation. This observation can be explained by QD saturation and an increase of uncorrelated background emission at high bias, which both limit the achievable SPE and result in an increase of $g^{(2)}(0)$ [2]. The highest
\( n_{SP\text{E}} \)-value in the SPS-regime \((g^{(2)}(0) < 0.5)\) amounts to \((47.0 \pm 6.9) \text{ MHz at } V_{DC} = 2.05 \text{ V}\). It is interesting to note that the achievable SPE rate of a given device depends sensitively on the particular settings of \(V_{DC}, V_{AC}\) and \(f\), for the latter even a resonance like dependence has been observed. In the present case we therefore fine-tuned the pulse frequency \(f\) which allowed us to obtain even higher values of \(n_{SP\text{E}}\) compared to 27.5 MHz reported in [5] for a 2 \(\mu\text{m} \) diameter SPS. The value \(n_{SP\text{E}} = (47.0 \pm 6.9) \text{ MHz}\) yields an overall SPS efficiency \(\eta = n_{SP\text{E}} / f = (21.4 \pm 3.1)\%\) when taking the repetition rate of \(f = 220 \text{ MHz}\) into account.

This finding can be classified by comparing the measured overall efficiency and the photonic outcoupling efficiency obtained indirectly by experimental cavity parameters. As derived in [3] the outcoupling efficiency \(\eta_{\text{ext}}\) of a SPS can be expressed by

\[
\eta_{\text{ext}} = \frac{Q_{\text{pillar}}}{Q_{2D}} \cdot \frac{F_P}{F_P + 1},
\]

where \(F_P\) denotes the Purcell factor and \(Q_{2D}\) represents the Q-factor of the planar microcavity. Taking the experimental values of \(Q_{\text{pillar}} = 2300, Q_{2D} = 3000\) and \(F_P = 4\) into account, we obtain an outcoupling efficiency of 61\% close to the maximum (70\%) derived in [3]. However, the overall efficiency of the SPS is strongly limited by a rather inefficient carrier injection into the QDs - a detrimental effect that can be attributed to non-radiative emission at the pillar sidewalls and the associated carrier losses [11, 12].

4. Summary

In summary we have presented electrically triggered SPE from a QD-micropillar with \(g^{(2)}(0)\) as low as 0.30\(\pm\)0.03. We demonstrated record high SPE rates of up to \((47.0 \pm 6.9) \text{ MHz}\) corresponding to an overall efficiency of \((21.4 \pm 3.1)\%\) for a 2.0 \(\mu\text{m}\)-diameter device.

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