Electrically Driven Single Photon Sources - Status and Challenges

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Abstract *Recent progress in the field of electrically pumped single photon sources based on quantum dot-microcavity systems will be reviewed. We demonstrate efficient single photon emission at rates exceeding 40 MHz from electrically pumped micropillar cavities.*

Introduction

The realization of efficient single photon sources (SPS) is a driving force in the development of quantum dot (QD) – microcavity structures. Motivated by a possible application in quantum communication systems a large number of quantum dot based SPS have been achieved [1-3]. Even though single QDs inherently act as single photon emitters due to their discrete energy level system they suffer from a pure out-coupling efficiency when embedded in a bulk semiconductor matrix as most of the isotropically emitted photons are trapped due to total internal reflection.

This efficiency is strongly enhanced for QDs embedded into high quality microcavities [4]. Here, a QD interacting resonantly with the cavity mode emits photons with high probability β into the latter before they leave the resonator owing to its photon capture time. The emitted photons will then be collected with a certain efficiency η, e.g., by an optical fiber. The extraction of photons usable for experiments is thus given by the product of β and η which is the SPS figure of merit and needs to be optimized by an appropriate device design. With this respect QD-micropillar cavities are attractive systems due to a high extraction efficiency approaching 70% as predicted by theory and a highly directional emission normal to the sample surface. Even higher values are expected in the photonic wire approach [5]. Experimentally, a high frequency SPS featuring an extraction efficiency of 38% in an optically micropillar system has been demonstrated [3].

Another important aspect in this field is the SPS pumping scheme. Up today most QD-SPS rely on optical pumping by an external laser source. This strongly hinders their application in practical devices for which a strong demand for compact electrically driven SPS does exist. However, up to now only a few approaches for electrically pumped SPS based on QDs embedded in oxide aperture pin-diodes with and without cavity effects and an efficiency of up to 17% have been demonstrated [6,7]. While comparatively simple technology can be used to contact this type of devices, it is significantly more demanding to apply electrical contacts to high quality (Q) – factor low mode volume (V_m) microcavities.

Recently, we succeeded in electrically contacting

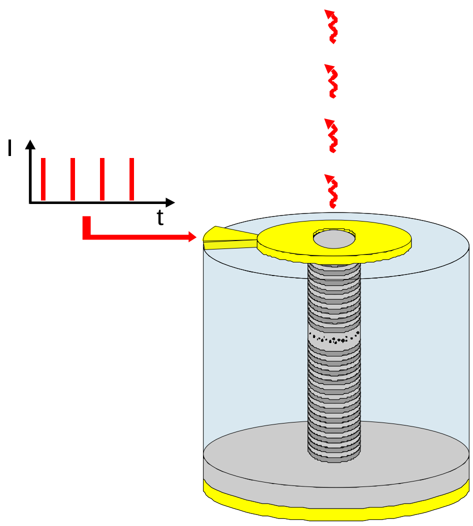

Fig. 1: Schematic view of an electrically pumped QD-micropillar single photon source.

high-Q micropillars with diameters down to 1 µm [8]. These structures show pronounced single QD cavity quantum electrodynamics (cQED) effects in the weak and the strong coupling regime as well as low threshold laser emission [9, 10]. Here, we will present highly efficient single photon emission from electrically driven QD-micropillar cavities (cf. Fig. 1). Single photon emission rates as high as 47 MHz and an extraction efficiency exceeding 40 % will be demonstrated.

Sample Technology

The electrically driven SPSs are based on a doped planar microcavity structure grown by molecular beam epitaxy on an n-doped GaAs substrate. The planar microcavity consists of a one-λ thick undoped GaAs cavity embedded between a lower n-doped distributed Bragg reflector (DBR) and an upper p-doped DBR composed of $\lambda/4$ thick AlAs/GaAs mirror pairs. In order to achieve a high outcoupling efficiency, an asymmetric layout with 13/26 mirror pairs in the upper/lower DBR has been chosen which results in a moderate Q-factor of 3000 for the planar microcavity. In the vicinity of the low density InGaAs QD layer in the center of the GaAs cavity an n-type δ-doped layer was introduced to eliminate dark-state configurations that are known to reduce the efficiency of SPSs based on neutral QDs [3]. Thus, electron–hole pair capturing owing to electrical excitation will create predominantly charged excitons (X^-) in a singlet configuration leading to fast recombination of the optically bright excitonic state.

The micropillars are manufactured by high resolution electron beam lithography and reactive ion plasma etching. Subsequently the pillar structures are planarized using benzocyclobutene (BCB). In a second electron beam lithography step, ring shaped top contacts are defined and formed by Au deposition. The geometry of the top contact leave the top facet of the micropillar free from any disturbing material and facilitates lateral current injection in the upper section of the micropillar as well as efficient in- and outcoupling of light. A cross sectional scanning electron microscopy (SEM) image of a fully processed device with a pillar diameter of 2.5 µm is depicted in Fig. 2. The device was cut by ion-beam milling in order to illustrate the sample layout.

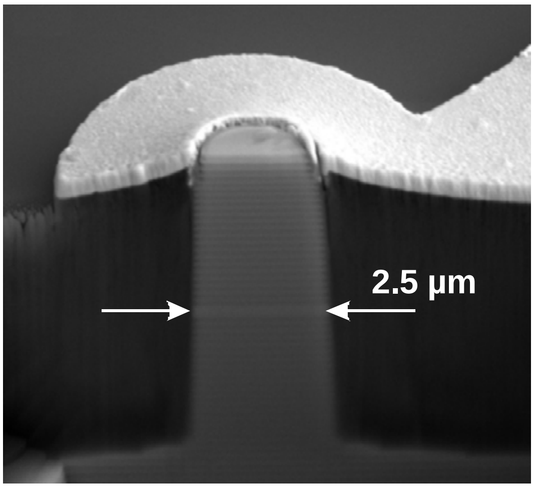

Fig. 2: Cross-sectional SEM image of a fully processed micropillar SPS. The micropillar with a diameter of 2.5 µm at is embedded into BCB acting as planarizer. The upper highly doped section of the micropillar is electrically connected by the ring-shaped Au contact. Ion-beam milling was used to prepare this structure for illustration.

Experimental

Single photon emission from the electrically contacted micropillars was investigated by means of high-resolution micro-electroluminescence (µEL) spectroscopy at low temperatures (10-70 K). The sample was mounted to the cold-finger of a He flow cryostat equipped with a precise temperature controller which allowed for resonance tuning experiments. The electroluminescence (EL) was collected by a microscope objective with an numerical aperture of 0.4, dispersed by a monochromator with a focal length of 0.55 m and detected by a Si-CCD camera. Single photon emission was probed using a fiber coupled Hanbury-Brown and Twiss (HBT) setup with Si-based avalanche photon detectors (APDs) acting as detectors. The overall temporal resolution of the HBT setup is approximately 0.7 ns. The sample was exited by an electrical pulse generator providing narrow pulses with widths down to 200 ps (FWHM) at a repetition rate of up to 200 MHz. In addition, a DC offset can be applied to the sample.

Fig. 3 shows µEL spectra of an electrically contacted micropillar with a diameter of 3 µm under pulsed excitation at 65 MHz. The device was biased with a DC voltage of 1.4 V, just below the onset of EL. In addition, pulses with an amplitude of 3 V were applied to obtain pulsed emission of light. In the off-resonance spectrum taken at 50 K a single, spectrally isolated QD exciton X as well as the fundamental cavity mode C with a Q-factor of 2200 can be identified. By increasing the sample temperature to 56 K the exciton X can be tuned into resonance with the cavity mode which is associated with a strong increase of the EL intensity due to an efficient coupling of excitonic emission into the cavity mode.

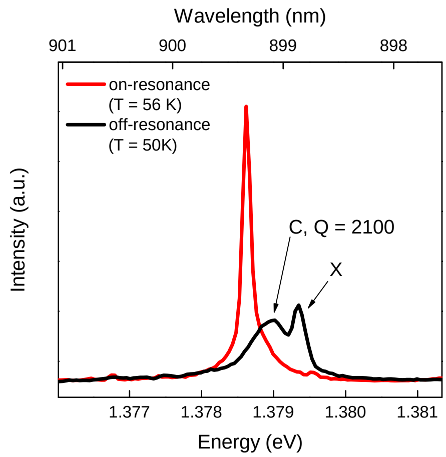

Fig. 3: Off- and on-resonance µEL spectra of an electrically contacted micropillar with a diameter of 3 µm under pulsed, electrical current injection at 65 MHz. At resonance with the cavity mode C the intensity of the single QD-exciton X is strongly enhanced due to cQED-effects.

The resonance behavior is demonstrated in the EL-intensity map of Fig. 4 in more detail over a wider range of temperatures. It is nicely seen that emission intensity increases significantly when the QD exciton is shifted into resonance with the cavity mode C. Interestingly, the cavity signal is hardly seen out of resonance. This is attributed to the moderate Q of the resonator and a low spectral density of off-resonance QDs that could illuminate the cavity mode by a yet not fully understood coupling effect that is very prominent in high-Q microcavity samples [11, 12].

We now address single photon emission from the micropillar under study. Figs. 3 and 4 demonstrate clearly that profound single QD interaction effects are observed in this device. To test the emission with respect to its photon statistics the EL was coupled to the HBT-setup which allows for the determination of the second order auto-correlation function $g^{(2)}(\tau)$, where single photon emission is characterized by $g^{(2)}(0) < 0.5$.

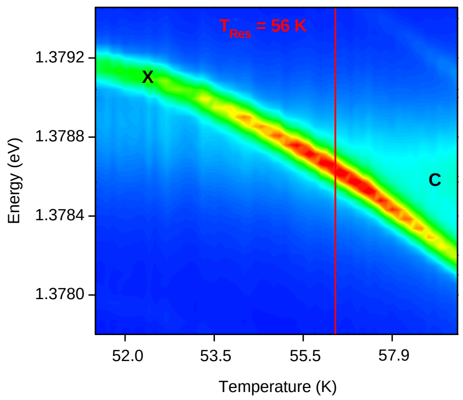

Fig. 4: µEL intensity map (pulsed excitation at 65 MHz) of the 3 µm diameter micropillar under variation of the sample temperature showing clearly the enhancement of emission when the QD exciton X resonantly coupled to the cavity mode C.

The photon autocorrelation function was measured at resonance (56 K) under pulsed excitation with a repetition rate of 102 MHz. Fig. 5 shows the corresponding time histogram. The periodic occurrence of coincidence peaks reflects clearly the pulsed emission of light from the sample. Furthermore, the strongly reduced peak at $\tau = 0$, i.e. photon antibunching, is a clear signature of the non-classical emission of light. In fact, the measured $g^{(2)}(0)$-value of 0.44 < 0.5 is an unambiguous proof of single photon emission from the QD-micropillar device. In order to explain the non-ideal $g^{(2)}(0)$-value we take uncorrelated background emission from the cavity mode into account. According to Michler et al. the expected correlation function $g_b^{(2)}(0)$ can be expressed via [13]

$$g_b^{(2)}(\tau) = 1 + \rho^2 (g^{(2)}(\tau) - 1) \qquad (1)$$

in the presence of background emission, where $\rho = S/(S+B)$ is the ratio of signal S to background B counts. For the present case we determine $\rho = 0.86$ by examining the on- and off-resonance spectra with leads to $g_b^{(2)}(0) = 0.26$ which partly explains the non-ideal $g^{(2)}(0)$-value. Further negative influence on $g^{(2)}(0)$ might be related to the impedance mismatch between the voltage source and the highly resistive micropillar device which could lead to multi excitation events during one excitation pulse.

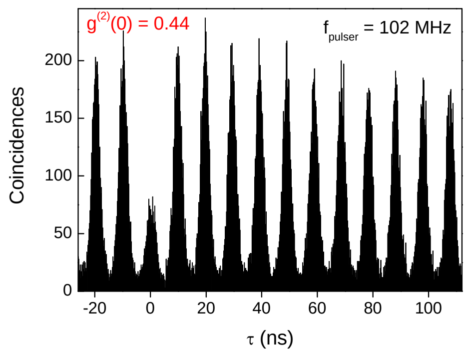

Fig. 5: Photon autocorrelation function of the electrically driven 3 µm diameter QD-micropillar under on-resonance condition and a repetition rate of 102 MHz.

It is interesting to estimate the outcoupling efficiency of the micropillar SPS and the single photon emission rate under electrically current injection. By a careful calibration of our experimental setup it is possible to estimate the single photon emission rate by the count rates of the Si-APD in the HBT-setup. In fact, the count rates of the APDs yield a rate of single photons emitted by the micropillar of 47±8 MHz at an excitation rate of 102 MHz. This result is in good agreement with an estimation of based on the cavity properties. As derived in Ref. 4 the outcoupling efficiency η_{ext} of a SPS can be expressed by

$$\eta_{ext} = \frac{Q_{pillar}}{Q_{2D}} \cdot \frac{F_P}{F_P + 1}, \qquad (2)$$

where F_P denotes the Purcell factor and Q_{2D} represents the Q-factor of the planar microcavity. Taking account experimental values of $Q_{pillar} = 2100$, $Q_{2D} = 2800$ and $F_P = 2$ determined from the temperature dependence of the exciton intensity in Fig. 4 we obtain an outcoupling efficiency of 50 %. This corresponds to a single photon emission rate of 51 MHz when driven at 102 MHz which is in good agreement with the value of 47±8 MHz determined directly from the experimental count rates. This numbers demonstrate clearly the potential of electrically pumped micropillars for highly efficient single photon sources.

Conclusions

In summary we have presented deterministic single photon emission from an electrically driven QD-micropillar. A record high single photon emission rate of 47± 8 MHz and an outcoupling efficiency of 50% were demonstrated for electrical excitation.

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