InP quantum dots in pillar microcavities — mode spectra and single–photon emission

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Abstract. We have investigated mode spectra and single–photon emission from InP quantum dots in a pillar microcavity. Micropillars are fabricated by milling a planar AlAs/AlGaAs cavity with a focused ion beam, containing self assembled InP quantum dots embedded in AlGaInP barriers as the active medium. We performed micro–photoluminescence measurements to characterize the mode spectra and compared them with a theoretical model revealing excellent agreement. Quality factors up to 3700 were achieved. Furthermore almost background–free single-photon emission was verified by second–order photon auto–correlation measurements under pulsed excitation, yielding $g(2)(0)$ values of 0.15.

1. Introduction
Micropillars (MPs) and microdisks containing quantum dots (QDs) are of high interest due to their potential of emitting single–photons [1, 2, 3].

QDs in the AlGaInP material system can be tailored to provide luminescence in the red spectral range (about 1.9 eV). This is the range of highest efficiency of typical silicon single–photon detectors, therefore InP QDs are ideal candidates for single–photon emission devices. QDs embedded in a resonant cavity allow highly directed single–photon emission, resulting in enhanced collection efficiency.

In addition, polymer optical fibers (POFs) also have their absorption minimum in the red spectral range. Therefore, InP QDs appear as very suitable light emitting media for the development of POF–based communication applications. Due to the large diameters of this type of fiber compared to common fiber optic cables, easy incoupling without additional optical components is possible.

Microcavities (MCs) are also interesting for all–optical switches and optical gate applications which will be necessary for quantum–computing and on–chip quantum–cryptography.

Stimulated emission of InP QDs in vertical cavity surface emitting lasers (VCSELs) was recently shown by our group [4].
2. Sample growth and preparation
The layer materials were deposited by using metal–organic vapor–phase epitaxy (MOVPE) at 750°C on (100)–oriented GaAs:Si substrate tilted by 6° toward the [111]A direction. 45 pairs λ/4–periods of Al0.5Ga0.5As:Si/AlAs:Si and 36 λ/4 thick pairs Al0.5Ga0.5As:C/Al0.95Ga0.05As:C were deposited as bottom and top distributed Bragg reflectors (DBRs) respectively, building up a planar cavity. The InP QDs were grown in Stranski–Krastanow growth mode [5] at 650°C, in spatial overlap with the E–field antinode of the fundamental planar cavity mode. ((Al0.2Ga0.8)0.51In0.49)0.5P0.5 was used as 10 nm thick barrier layer around the QDs, ((Al0.55Ga0.45)0.51In0.49)0.5P0.5 completes the λ–cavity as a cladding layer.

Finally, the circularly shaped MPs with diameters between 0.6 and 5.7 µm were milled out of the planar cavity by a focused ion beam (FIB). By final polishing steps at decreasing ion energies, MP structures with very smooth sidewalls could be achieved (see Fig. 1).

![Figure 1. Scanning electron microscope image of a 5.7 µm diameter micropillar (MP) cavity, fabricated by focused ion beam etching.](image_url)

3. Measurement setup
The mode–spectra were investigated using an micro–photoluminescence (µPL) measurement setup, with a super–continuum fiber laser as the excitation source (pulsed mode). The excitation wavelength of 570 nm was selected by an acousto–optic tunable filter with a spectral bandwidth ∆λ = 3 nm. The luminescence of the sample was collimated by a 50× objective and spectrally resolved by a 500 mm spectrometer with a 1200 lines/mm grating and an attached charge coupled device camera (1024 pixel columns), resulting in a spectral resolution better than 100 µeV. The sample was mounted in an evacuated He–flow cryostat at a temperature of 4 K.

For auto–correlation measurements, the spectrally pre–filtered emitted light was sent to a Hanbury Brown and Twiss setup consisting of a nonpolarising 50/50 beam splitter cube (NPBS) followed by two avalanche photon diodes (APDs) in the two detection arms of the beam [6]. Temporally correlating the detection events of the APDs allows photon statistics measurements, revealing the g(2)(τ) function over short timescales τ, which can therefore be used as a proof of single–photon emission.

4. Mode spectra calculation
To obtain the cavity modes of the MC, the longitudinal modes of the planar resonator structure are calculated via the transfer-matrix method, giving the electric field amplitude in the direction perpendicular to the layers. An effective refractive index n_{eff} averaging over the entire pillar
cavity is then obtained by weighting the refractive index at each point in space with the corresponding longitudinal electric field amplitude.

The electromagnetic field in lateral direction may now be calculated by modeling the pillar MC as a homogeneous dielectric waveguide of cylindrical shape with effective index of refraction \( n_{\text{eff}} \). Solving the transverse wave equation, we finally determine the cavity modes of the pillar, as depicted in Fig. 2. The modes are denoted as \( \text{EH}_{x,y} \) and \( \text{HE}_{x,y} \) which are hybrid modes of TE– and TM–modes [7].

5. Micro–PL spectroscopy results

In Fig. 2 a typical MC mode-spectrum (black line) is shown. Beginning on the low energy side, the fundamental \( \text{HE}_{1,1} \)–mode of the MC is visible, followed by higher transverse modes which can be identified by our theoretical model as hybrid TM/TE modes \( \text{HE} \) (red markers) and \( \text{EH} \) (blue markers) [8, 9]. The measured spectra reveal excellent agreement with the theoretical model.

![Figure 2. µPL mode spectrum of a 5.7 µm diameter micropillar cavity under pulsed excitation at 570 nm (black line). The theoretically calculated mode energies are shown as vertical markers (red: \( \text{HE}_{x,y} \)–modes, blue: \( \text{EH}_{x,y} \)–modes). Numbers are indicating the order of the modes \((x, y)\).](image)

Quality factors of these MCs reach up to \( Q = \frac{\lambda}{\Delta\lambda} \approx 3700 \) for a 5.7 µm pillar as derived from the fundamental \( \text{HE}_{1,1} \)–mode, whereas reflectivity measurement of an unprocessed sample area reveal a quality factor of 5300 for the planar mode [10].

6. Autocorrelation measurement

Single–photon emission of the fundamental mode of a MC with a diameter of 1.26 µm was observed in \( g^{(2)}(\tau) \) photon autocorrelation measurements under pulsed excitation into the AlGaInP barrier. In Fig. 3 the emission of the fundamental mode which was spectrally filtered for the measurement is indicated by arrows. The autocorrelation measurement yields a Poisson–normalized value of \( g^{(2)}(\tau = 0) = 0.15 \pm 0.0 < 0.5 \) which clearly identifies the emission to originate from a triggered single quantum–emitter [11]. (right figure)

The \( g^{(2)}(\tau = 0) \) value of 0.15 may result from detector limitations and signal background. Taking the signal \( (S) \) to background \( (B) \) ratio \( \rho = S/(S+B) = 0.92 \) into account, a background–corrected \( g^{(2)}(\tau = 0) \) [11] results in \( g_b^{(2)}(\tau = 0) = 1 - \rho^2 = 0.15 \). Therefore single–photon emission is demonstrated.
Figure 3. Left side: PL spectrum of a 1.26 µm micropillar cavity fundamental mode under pulsed excitation at 4 K. Right side: Autocorrelation measurement of the spectrally filtered mode emission at 4 K, marked by red arrows in the left figure. A background contribution of 8% to the left shown peak is clearly visible (indicated as red box), resulting in $g^{(2)}(\tau = 0) = 0.15$.

7. Conclusion

AlGaAs-based micropillars containing InP QDs exhibit high $Q$–factors up to 3700 were fabricated using focused ion beam milling. We have shown excellent agreement of the mode energies derived from theoretical model calculations with our measured data. Almost background–free single–photon emission in the red spectral range ($\sim 1.87$ eV) from individual InP quantum dots inside the micropillars was verified by photon autocorrelation measurements.

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