Manipulating the optical properties of CdSe/ZnSSe quantum dot based monolithic pillar microcavities

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Abstract. A customization of the optical properties of pillar microcavities on the desired applications is essential for their future use as quantum-optical devices. Therefore, all-epitaxial cavities with CdSe quantum dot embedded in pillar structures with different geometries have been realized by focused-ion-beam etching. The quality factors of circularly shaped pillar microcavities have been measured and their dependence on the excitation power is discussed. As a possibility to achieve polarized light emission, asymmetrically shaped microcavities are presented. Examples of an elliptically shaped pillar as well as of photonic molecules are investigated with respect to their photoluminescence characteristics and polarization.

1. Introduction
For several years the steady improvements in preparation techniques allow for sophisticated confinement of light on the wavelength scale [1]. With structuring methods like lithography or focused-ion-beam etching (FIB) a high flexibility concerning the shape of the etched microcavities (MCs) is achieved [2]. In case of embedded quantum dots (QDs) in a MC this allows for a tailoring of the optical emission properties which is promising for applications in new quantum-optical devices such as low-threshold lasers and efficient single-photon sources [3][4]. As a high temperature insensitivity of the QD emission is desirable, the II-VI material system with its remarkable stability of the excitonic QD emission is the material of choice [5]. An important figure of merit of a cavity is the quality factor $Q = E/\Delta E$ (with $\Delta E$ being the emission linewidth and $E$ its energy). It describes the optical energy stored in the resonator divided by the energy loss during one oscillation period of the light within the cavity. In the following, we report on the dependence of the quality factor on the excitation power. We describe methods for a spectral tuning of the QD emission and of the fundamental mode (FM) in MCs. Further, attempts to achieve polarized light emission are discussed.

2. Experimental
Planar MC samples were grown by molecular beam epitaxy on GaAs substrates at a temperature of 280°C. The ZnSSe $\lambda$-cavities contain either one single or five sheets of CdSe/ZnSSe QDs grown by migration enhanced epitaxy. For an enhanced temperature stability of the excitonic emission the QDs are embedded in between additional MgS barriers. The cavities are positioned in between a 18.5 period bottom and a 15 period top distributed-Bragg-reflector (DBR) stack.
Completely etched cylindrically shaped pillar MCs with diameters between 1 and 4 μm were prepared from the planar cavities by focused-ion-beam etching using a FEI Nova NanoLab system [7]. For investigations of polarized light emission elliptically shaped MCs as well as photonic molecules, consisting of two cylindrically shaped pillars connected by a small bar, were milled. A micro-photoluminescence (μ-PL) setup has been used employing a microscope objective to excite individual pillar structures and to collect their emission. The measurements were performed at variable temperatures using a cw Ar laser with 2.71 eV or a frequency doubled Ti:Sa laser operating at 2.71 eV or 3.10 eV emission energy as excitation sources, respectively. The PL emission was detected either by a nitrogen cooled charge-coupled device camera (CCD) or a multichannel plate after dispersion in a monochromator. For polarization dependent measurements a polarizer and a λ/2 waveplate were inserted into the detection beam line.

3. Results
The investigated samples are characterized by Q factors of up to 7860 determined from the fundamental mode (FM) of circularly shaped airpost pillar MCs. Furthermore, an effective Purcell factor of up to 4 was determined earlier by lifetime measurements of the QD emission in resonance to the FM when compared to the data obtained for leaky modes [9].

In Fig. 1, the fundamental and two higher-order modes of a microcavity structure with a pillar diameter of 1.93 μm and 5 QD layers as active material are displayed. The structure has been designed such that the longitudinal resonance of the cavity and the emission band maximum of the QD ensemble coincide at T = 4 K. The PL intensity of the modes is shown for three different mean excitation powers under pulsed excitation. With rising excitation power the PL intensities of the resonator modes show a linear increase. The corresponding quality factors of the FM and the first higher-order mode (M1) as well as the PL intensity of the FM are plotted versus the excitation power in Fig. 2. The quality factors of the FM and M1 rise with increasing excitation power until they saturate at a mean excitation power of around

![Figure 1.](image1.png)  
**Figure 1.** PL intensity of the energetically lowest modes for mean excitation powers of 0.3 (blue), 0.7 (red) and 1.6 (black) μW. The pillar diameter is 1.93 μm. T = 4 K.

![Figure 2.](image2.png)  
**Figure 2.** Quality factor Q (left scale) of the FM (red dots) and M1 (black squares). PL intensity of the FM (blue triangles, right scale) in dependence on excitation power. The solid lines correspond to a fit (see text).
0.4 μW (13 kW/cm$^2$). The solid lines represent a fit to the experimental data which reflect the influence of absorption losses within the cavity on the quality factor by the equation: $1/Q = 1/Q_{\text{int}} + 1/Q_{\text{abs}}$. $Q_{\text{int}}$ and $Q_{\text{abs}} = 2\pi n/\alpha \lambda$ are the intrinsic quality factor and the quality factor resulting from the absorption losses at the resonant wavelength [8], respectively. At low excitation power the internal absorption losses lower the $Q$ factors. Since these internal absorption losses are compensated at higher excitation densities, $Q_{\text{abs}}$ will steadily increase. Finally, $Q_{\text{int}}$ will dominate the expression for the total $Q$. The saturation of the fundamental mode PL intensity is most probably due to heating effects at elevated excitation densities.

For effective devices it is important to enhance the collection efficiency of the emitted photons by achieving a perfect spectral overlap of the QD emission and the FM. One easy and non-permanent method is the change of the sample temperature. Due to its correlation on the bandgap, the QD emission energy depends stronger on the temperature than that of the FM determined by the much weaker change of the refractive index with temperature. Hence, the ultrasharp QD emission can successively be shifted into resonance with the cavity mode by temperature tuning. Thus the PL intensity of a QD in resonance with the FM was increased by a factor of five compared to the off-resonance case, demonstrating the much larger coupling of the QD luminescence into the FM.

As the spectral position of the FM strongly depends on the pillar diameter, a post-processing FIB reduction of the pillar diameter represents a permanent possibility to bring the QD emission in resonance with the FM. The FM of a pillar with originally 1.18 μm diameter was shifted towards the QD emission by a diameter reduction of 90 nm. A fivefold increase of collection efficiency could thus be achieved [7].

The ability to realize structures that emit polarized light is highly desirable for applications like quantum information processing. Therefore, the polarization properties of the resonator mode emission are investigated for different pillar geometries. The FM of circularly shaped pillars is generally spectrally twofold degenerate [10]. However, in some samples an energy splitting of the FM of up to 0.5 meV has been observed and assigned to a strain-induced variation

![Figure 3](image-url). Elliptically shaped MC: PL intensity for two orthogonal settings of the polarizer at $T = 4 \text{K}$. The splitting of the FM is 4.47 meV. In the inset an SEM image of the elliptically shaped pillar MC is shown.

![Figure 4](image-url). Molecule-like MCs: PL intensity for two orthogonal settings of the polarizer at $T = 4 \text{K}$. The splitting of the FM is 670 μeV. In the inset an SEM image of the photonic molecule MC is shown.
of the index of refraction in certain crystallographic directions (see [11], and references therein). A possibility to intentionally achieve polarized light emission is the use of asymmetrically shaped MCs of which elliptical MCs are best known [12]. The geometric asymmetry lifts the polarization degeneracy of the FM which splits into two modes with orthogonally orientated polarization. The polarization dependent PL of an elliptically shaped MC with axis lengths of 1.74 μm and 3.58 μm, respectively, is shown in Fig. 3 (SEM image of the MC in the inset). A clear separation of the FM (4.47 meV) as well as of the first-order mode is observed for the two orthogonal polarizations of 0° and 90° leading to a nearly 100% polarized light emission of the FM. Although the quality factors should, in principle, reach higher values compared to circularly shaped MCs [12], this was not seen in the experiment due to a higher sidewall roughness resulting from the different FIB-structuring method needed for milling asymmetrically shaped pillar MCs.

The highly flexible FIB etching also allows to create more sophisticated structures, for example, so-called photonic molecules [2]. They consist of several MC pillars which are connected by small bars. A photonic “diatomic” molecule was fabricated consisting of two pillars with diameters of 1.7 μm each for studying the polarization dependent emission. The pillars are connected by a bar of 0.64 μm length and 0.53 μm width. The normalized PL spectra of the FM for the two orthogonal polarizer settings of 0° and 90° is plotted in Fig. 4. The inset shows an SEM image of the photonic molecule. A clear dependence of the FM energy position on the chosen polarizer setting is observed. A splitting of the FM of 670 μeV between the two orthogonal states has been measured. This shows that photonic molecules likewise offer the ability to achieve polarized light emission.

4. Conclusions

We successfully fabricated high-Q monolithic II-VI airpost pillar microcavities for the green spectral region out of MBE grown planar samples by FIB milling. Rather large quality factors Q have been obtained. For the determination of the correct intrinsic quality factors the internal losses have first to be compensated. A considerable increase of the PL intensity could be achieved by tuning the QD emission and the FM in resonance. Multiple ways were shown for achieving polarized light emission from MCs including asymmetrically shaped pillars and molecule-like pillar structures were shown.

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