Polarized light emission from CdSe/ZnSSe quantum-dot monolithic pillar microcavities

Moritz Seyfried\textsuperscript{1}, Joachim Kalden\textsuperscript{1}, Kathrin Sebald\textsuperscript{1}, Arne Gust\textsuperscript{2}, Carsten Kruse\textsuperscript{2}, Detlef Hommel\textsuperscript{2}, and Jürgen Gutowski\textsuperscript{1}

\textsuperscript{1}Semiconductor Optics, Institute of Solid state Physics, University of Bremen, Germany
\textsuperscript{2}Semiconductor Epitaxy, Institute of Solid state Physics, University of Bremen, Germany
E-mail: Seyfried@ifp.uni-bremen.de

Abstract. Small-size II-VI micropillars with asymmetrical cross sections are presented as a way to achieve more than 95\% of the emitted light from single quantum dots having one particular linear polarization state. We show that the detected PL intensity of the QD is increased by optimizing the spectral overlap between QD emission and resonator mode. The polarization of the emitted light is defined by the polarization of the resonator mode. Moreover, the internal mode structure in photonic molecules is investigated by studying their far field pattern. The observed field distribution opens the possibility of coupling individual quantum dots to each other via the mediation of the electromagnetic field.

1. Introduction
Future applications in the field of quantum information processing like, e.g., quantum computing or quantum cryptography will be based on robust and reliable single-photon sources [1]. In recent years, self-assembled semiconductor quantum dots (QDs) have been confirmed to act as single-photon sources [2]. By embedding these QDs into small-volume and high-quality pillar microcavities (MCs) the spontaneous emission rate can be enhanced and the collection efficiency increased [3]. However, for quantum information processing it is also crucial to control the polarization state of the emitted photons. This may be achieved by altering the shape of the micropillars, leading to a control of the photonic mode structure to some extent [4]. With this technique a polarized QD emission could be shown for elliptically shaped MCs in the III-V material system [5][6]. Furthermore, the coupling of different QDs is of high interest for the generation of entangled photons which can also be achieved via the electromagnetic field in a cavity. As temperature insensitivity of the QD emission is desirable, the II-VI material system with its remarkable stability of the excitons in the QDs is the material of choice [7][8].
In the following, we show for the II-VI material system that the intensity ratio between different polarizations of the QD emission can be controlled by using asymmetrically shaped MCs and can be changed by temperature detuning of the QD against the cavity mode. Furthermore, photonic molecules (PMs), consisting of two circularly shaped MCs which are interconnected by a small bar, are presented as a possibility to couple individual QDs and discussed with respect to their far field pattern [9].
2. Experimental
Planar MC samples were grown by molecular beam epitaxy on GaAs substrates at a temperature of 280 °C. The ZnSSe λ-cavity contains one sheet 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 cavity is positioned in between an 18.5 period bottom and a 15 period top distributed-Bragg-reflector (DBR) (details in [10]). The structures have been designed such that the spectral position of the longitudinal resonance of the cavity and the low-energy tail of the QD ensemble coincide at 4K. For investigations of polarized light emission, completely etched elliptically shaped pillar MCs as well as photonic molecules were prepared from the planar sample by focused-ion-beam etching using a FEI Nova NanoLab system [11]. A micro-photoluminescence (µ-PL) setup with a nitrogen cooled charge-coupled camera (CCD) has been used while 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 at 2.71 eV excitation energy. For polarization dependent measurements a polarizer and a λ/2 waveplate were inserted into the detection beam path. The far field pattern was obtained with the same setup by measuring sequences of 1D spatial profiles corresponding to a cut through the far field. The final 2D far field pattern was obtained from these individual 1D profiles by using a computational routine.

3. Results
The samples are characterized by Q factors of up to 7860 determined from the fundamental mode (FM) of circularly shaped airpost pillar MCs [10]. In the inset of Fig. 1 the photoluminescence spectrum of an elliptically shaped MC is shown with axis lengths of 1.89 µm and 3.89 µm, respectively. For a better identification of the modes the whole spectrum was measured at an elevated temperature of T=80 K at which the spectrally broadened emission lines of the QDs act as internal light source for the cavity modes. If the measurement is performed for two orthogonal polarizer orientations of 0° and 90°, defined by polarizer settings parallel to the short and long axis of the ellipse, respectively, the polarization degeneracy of the modes is lifted.

![Figure 1. Polarization resolved PL spectra for 0° and 90° polarizer orientation of an elliptically shaped MC with axis lengths of 1.89 µm and 3.89 µm at T = 4 K. In the inset a much extended spectrum is shown at T=80 K.](image1)

![Figure 2. Single line emission of a QD at temperatures between 4K to 25K and a polarizer orientation of 0°. The spectral position of the mode is marked with the arrow in the inset of Fig. 1](image2)
due to the asymmetric cross section. Thus, an energy splitting between orthogonally polarized mode components becomes visible. Spectrally sharp and partially resolution limited emission lines from the QDs are visible over the whole spectral range in particular at low temperatures. The collection efficiency of a QD can be dramatically increased by optimizing the spectral matching with a cavity mode [12]. The marked section of the inset was measured polarization resolved at $T=4 \text{K}$ and is shown in the main frame of Fig. 1. The polarization orientation of the underlying mode leads to the enhancement of each QD emission in the same polarization direction and to the suppression of the emission into the orthogonal direction and hence to a polarized QD emission. In Fig. 1, QDs emitting in the spectral regime from 2.260 eV to 2.264 eV are more pronounced for the polarizer orientation of 90$^\circ$, in contrast to another set of dots in the spectral region between 2.267 eV to 2.271 eV which gains intensity for the polarizer orientation of 0$^\circ$. Comparing the PL intensity of one distinct QD for both polarizer orientations we observe a strong enhancement of the emission into one mode while the emission into the corresponding orthogonally polarized mode is suppressed. This yields, e.g., a polarization degree of 83\% for the QD emitting at 2.2615 eV.

The redshift of the modes with increasing temperature due to an increase of the refractive index is small compared to the band gap shrinkage. Thus, the variation of the QD transition energy with temperature can be used to tune the QD emission into resonance with the modes of the cavity and thereby to enhance the QD emission. This is shown in Fig. 2 for a QD and the resonator mode at about 2.255 eV under 0$^\circ$ detection. The QD emission is shifted starting with a small detuning of -90 $\mu$eV ($T=4 \text{K}$), going into resonance with the cavity mode at $T=15 \text{K}$, and off resonance again with a positive detuning at $T=25 \text{K}$. For a QD in a spectral region where one polarized mode completely dominates (e.g., the region from 2.260 eV - 2.264 eV in Fig. 1) we can thus systematically change the intensity of the QD emission into this mode. At the same time the emission with orthogonal polarization remains on a constant rather low intensity level.

Figure 3. SEM image and two-dimensional spatial distribution of the PL intensity (red highest) of the fundamental mode as well as the first and second higher-order modes of a photonic molecule. The images were taken at the spectral position of the assigned modes in Fig. 4.

Figure 4. PL spectra of the photonic molecule shown in the SEM image of Fig. 3 measured at $T=4 \text{K}$. The labels on the modes correspond to the displayed far field pattern.
since for this polarization direction no active resonator mode is interacting with this emission. Thus, the polarization degree of the detected photons from the QD is considerably increased. Here, for zero detuning between the QD emission and the cavity mode we thus found 95% of the QD emission to couple into the 90° polarized mode.

Microcavities can also yield a coupling of different QDs by the mediation of the electromagnetic field. To study this effect, we produced several photonic molecules with different distances between the two circular pillars. The asymmetric total shape lifts the polarization degeneracy of the modes and leads to an energy splitting of up to 870 µeV for the FM of the PM with pillar diameters of 1.7 µm each and a bar of 0.64 µm length and 0.53 µm width. In Fig. 3 an SEM image of such a photonic molecule and the corresponding far field images of the fundamental mode (I) and two higher-order modes (II, III) are shown. All measurements were performed under excitation into the center of the PM. For a better understanding of the far field pattern the corresponding PL spectra of the PM with the first three modes numbered is presented in Fig. 4. The FM has its spatial intensity distribution maximum right in the middle of the PM whereas the first higher-order mode has two peaks locally shifted towards the individual pillars. The second higher-order mode possesses three intensity maxima, one in the center of the PM and the two others close to each pillar center. These first and second higher-order modes therefore could offer a possibility to couple two QDs each one located in one of the both pillars via the electromagnetic field [13][14]. The measurements further show the coexistence of localized (fundamental mode) and delocalized modes (next two higher-order modes) in the same microcavity. In combination with a method to tune the QDs’ emission on and off such a resonance a switchable coupling of two QDs may be achieved.

4. Conclusions
We successfully fabricated asymmetrically shaped microcavities out of MBE grown planar samples by FIB milling. For the elliptically shaped pillars as well as for the photonic molecules a lifting of the polarization degeneracy of the fundamental cavity mode was observed leading to a more than 95% linear polarization for some QDs. The far field pattern of PMs shows the spread of the electromagnetic field over the whole molecule for some modes making these PMs interesting candidates for investigations concerning the coupling of several QDs.

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