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Enhanced correlated photon pair emission from a pillar microcavity

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Abstract. We demonstrate the efficient generation of triggered photon pairs by placing a single quantum dot (QD) into a micropillar cavity. Photon crosscorrelation measurements between biexciton and exciton decay reveal a bunching effect under pulsed excitation due to the cascaded nature of the emission. No polarization correlation between the exciton and biexciton emission is observed. Furthermore, the emission mode structure of the pillar microcavities is investigated within a theory-experiment comparison where calculations are based on an extended transfer matrix method. Efficient mode confinement perpendicular to the emission direction leads to a series of transverse modes combined with enhanced QD emission. For the photoluminescence (PL) intensity of QDs in pillar microcavities ($0.6 \,\mu$ m diameter), an enhancement factor of 40 was found in comparison to the PL intensity of QDs in bulk semiconductors, reflecting the enhanced photon collection effect out of the cavity structure.

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1. Introduction

Recently, quantum dots (QDs) have been used to demonstrate single photon emission [1]–[3]. Single photons and correlated photon pairs on demand are particularly useful for future applications in quantum information technology, e.g. quantum cryptography and quantum computation [4]. The great advances in nanotechnologies make it possible to fabricate low-dimensional structures where both electrons and photons are confined. On the one hand, QDs offer several advantages as a source of single photons; they have large oscillator strengths, narrow spectral linewidths, long-term stability and can be easily integrated in a device structure. On the other hand, only very few of the emitted photons escape in any given direction due to the high refractive index contrast between the semiconductor containing the dots and the air. This problem can be solved, however, by embedding the dots in an appropriate microcavity [5, 6]. In quantum optical devices, microcavities can guide the emitted photons from QDs in a desired direction. In practice, the emission energy of the QD should be in resonance with a mode of the microcavity to achieve high collection efficiency.

Investigations of the photon statistics have been performed for various types of semiconductor microcavities. For example, Michler *et al* [1] have achieved single-photon emission in a microdisk, Pelton *et al* [5] and Moreau *et al* [6] have demonstrated the efficient generation of single photons using a single QD in a micropost cavity. In addition, radiative quantum cascades between biexcitons (XX) and excitons (X) have been studied on single QDs embedded in bulk materials [7, 8, 10, 11] and microdisk structures [9]. Furthermore, the polarization correlation properties of such photon pairs from an individual InAs QD [7, 10] and a CdSe QD [11] have been reported.

This paper is organized as follows: our investigated pillar microcavity sample and the experimental procedure are briefly described in section 2. The study of pillar microcavities is performed in section 3: we will discuss the pillar microcavity modes within a theory–experiment comparison for larger diameter pillars. We also demonstrate the emission of single QDs from smaller diameter pillars. The luminescence intensity from a QD in bulk and in a pillar microcavity is compared. At the end of this section we will show a two-photon density matrix in which an experimental study of the polarization cross-correlations of photon pairs emitted by a biexciton–exciton cascade from a single QD in a pillar microcavity structure is presented. The conclusions are given in section 4.

2. Sample structures and experimental set-up

The investigated pillar microcavity sample was grown by molecular beam epitaxy (MBE) on a (100)-oriented undoped GaAs substrate, with a buffer layer of $0.4 \,\mu$ m. A schematic representation





Figure 1. Schematic representation of the sample structures under investigation.





of the sample structure is shown in figure 1. A GaAs cavity layer is sandwiched between the bottom and top distributed Bragg reflectors (DBRs), which consist of 23- and 20-period AlAs/GaAs layers, respectively. Each DBR pair consists of a 79-nm-thick AlAs and a 67nm-thick GaAs layer. A 1.4 nm thick single layer of self-assembled (In, Ga)As/GaAs QDs is used as the active region and is inserted at the centre of the cavity. The QD surface density is $\approx 3 \times 10^{10}$ cm⁻². Pillar microcavities with different diameters ranging from 0.2 up to 6.0 μ m and spaced 400 μ m apart were fabricated by electron beam lithography and dry etching. Figure 2 illustrates a scanning electron microscope (SEM) micrograph of typical AlAs/GaAs pillars. In this picture two different pillar sizes are visible, the larger structure has a diameter of 6 μ m and the smaller one has a diameter of 0.3 μ m with a height of 3.4 μ m (only three layers of the bottom DBR have been etched away). The pillar sidewalls are nearly vertical with only small damages appearing next to the top surface.

Our experimental set-up consisted of a combined low-temperature (4 K) microphotoluminescence (μ -PL) set-up and a Hanbury-Brown and Twiss (HBT) set-up [12] for

photon correlation measurements. The sample was mounted in a He-flow cryostat which can be moved by computer-controlled xy-linear translation stages thus allowing for scanning across the sample with a spatial resolution of 50 nm. The QDs were excited by a Ti:sapphire laser either operating in continuous wave (cw) or pulsed mode ($\Delta t_{pulse} \approx 2 \text{ ps}$ pulse width at $f_{rep} = 76.2 \text{ MHz}$). To preferably pump the InGaAs QD layer and also effectively suppressing contributions from the GaAs barrier, the laser was tuned to 868 ± 2 nm in the wetting layer continuum thus resulting in an almost background-free QD signal as will be shown in the following. For the excitation of our sample structure the laser light was focused to a spot diameter of $\approx 10 \,\mu$ m in a steep angle (30°) geometry using a lens-equipped optical fibre set-up. A microscope objective (a numerical aperture NA = 0.5) was then used to collect the QD emission. The collected luminescence was then either spectrally filtered by a 1 m monochromator equipped with a charge coupled device (CCD) for PL measurements or sent directly to our HBT set-up for investigations on photon statistics. The HBT consisted of a 50/50 non-polarizing beam splitter, two acousto-optic tunable filters (AOTFs) and two single-photon counting avalanche photodiodes (SAPDs) each providing a time resolution of \sim 700 ps. The SAPDs output signals were used to trigger the start and stop channels of a time-to-amplitude converter (TAC) the output of which was stored in a PC-based multichannel analyser (MCA). In this way, a histogram $n(\tau)$ of photon correlation events as a function of the time delay $\tau = t_{stop} - t_{start}$ was recorded. In our experiments, an electronic delay of 28 ns was added on the stop channel thus allowing to record negative as well as positive values of τ . The AOTFs were placed inside the two optical arms of the HBT set-up, where each filter could be used to select a specific emission line within the overall spectral range from 900 to 1000 nm (filter bandwidth $\Delta\lambda \approx 1.1$ nm). The selected spectral window of detection, however, in most cases appeared to be significantly larger than the typical measured (resolution limited) linewidths of individual QDs ($\sim 0.04-0.06$ nm) in our sample.

3. Results and discussions

Within a theory-experiment comparison we have studied the emission properties of semiconductor QDs in pillar microcavities of different nominal diameters. Especially for larger pillars the typically huge number of enclosed QDs emitting an inhomogeneously broadened PL spectrum (due to their size distributions) provide an 'built-in' light source to investigate the mode structure of the surrounding cavities. To allow for a comparison of our experimental results with theory, the mode structures of the pillar microcavities were determined from a solution of vector Maxwell equations for a three-dimensional geometry under the assumption of an ideal cylindrical pillar symmetry. In the present model, the surface roughness and the finite etching depth were not taken into account. Following Burak and Binder [13] we expand the electric and magnetic field in each pillar layer (\equiv disk) with respect to the modes of a cylindrical optical waveguide. In the numerical computation a finite number N of modes in each waveguide is considered. The expansion coefficients of neighbouring layers are related due to the continuity of the transverse components of the electric and magnetic fields at the layer interfaces. Therefore, a relation between the fields for the topmost and the lowermost pillar layer can be finally expressed in terms of a $2N \times 2N$ transfer matrix. It is worth noting that conventional 2×2 transfer matrices can only be applied to *one-dimensional* geometries and therefore describe only the mode structure in the *longitudinal* direction (i.e. perpendicular to the layers). In contrast



Figure 3. (a) Calculated 2D transverse electric field patterns corresponding to various pillar modes in the theoretical (solid line) and experimental (dashed line) 6 μ m pillar spectra in (c). The degeneracy of each mode is indicated (e.g. $2 \times \equiv$ two-fold). (b) Spectrally resolved 1D charge-coupled device image of the 6 μ m pillar mode structures. (d), (e) Theoretical (----) and measured (----) cavity spectra for decreasing pillar diameters of 5 and 4 μ m, respectively.

with that, the generalized transfer-matrix method also provides the *transverse* mode structure. The method is exact as long as all waveguide modes are included in the expansions. However, for practical reasons, waveguide modes which are unbounded in the transverse direction are ignored. This approximation is justified for pillars with large diameter because radiation in the transverse direction is negligible in this case. On top of this approximation, Burak and Binder [13] propose a so-called common-mode approximation where only waveguide modes with the same mode numbers are coupled across interfaces. We have found that results with and without the common-mode approximation are almost identical for larger pillar diameters ($\geq 2 \mu m$). For this situation it justifies earlier investigations [14] based on a decoupling of TE and TM modes.

In figure 3(a) the full calculated transverse electric field patterns for the various modes of a $6 \mu m$ diameter pillar structure are shown which correspond to the peaks in the calculated (solid line) and measured (dashed line) cavity spectra in figure 3(c), respectively. For comparison, in figure 3(b), the spectrally resolved CCD image of these $6 \mu m$ cavity modes as obtained under

pulsed excitation is given. Considering the CCD image to represent an one-dimensional (1D) 'cut' through each individual mode pattern, a high degree of consistency becomes obvious. Starting from the fundamental pillar mode (figure 3(a)) at \sim 913.4 nm, revealing a centre-peaked field pattern, a ring-structured distribution of increasing diameter is expected for higher modes. In fact, this effect is reflected in the 1D CCD images where a pronounced peak splitting is revealed for higher modes. Also, from a comparison of the energetic mode spacing (see figure 3(c)) good agreement with the theory (solid line) is found, thus confirming the peaks' nature as different transverse modes in the micropillar.

Since the cavity was grown in a wedge-like shape, various positions on the wafer correspond to different resonance wavelengths. Accordingly, the thickness of the spacer and mirror layers was adjusted in the calculations (with an unchanged thickness ratio of various layers) to match the experimental position of the resonance wavelength for the fundamental mode (first peak from the right). For the refractive indices of various materials $n_{GaAs} = 3.52$, $n_{AlAs} = 2.92$, and $n_{InAs} = 3.6$ were used. To find good agreement with regard to the spacing between peaks we have chosen a slightly larger diameter pillar of 6.2 μ m (figure 3(c)). The fundamental mode is two-fold-degenerate due to different azimuthal quantum numbers (see figure 3(a)). In contrast with that, the second peak from right consists of a two-fold-degenerate mode and two almostdegenerate single modes. The third peak from right accommodates two modes each of which is two-fold-degenerate. The fourth peak is two-fold degenerate. The fifth peak consists of two modes each of which is two-fold degenerate. The degeneracy of all contributing modes is reflected in the height of the corresponding peaks in the calculated spectrum. Note that the different heights of the experimental peaks reflect the distribution of underlying inhomogeneously broadened QD emission centred around the fundamental mode. The calculated quality factor $Q \sim 30\,000$ for the fundamental mode exceeds the experimental value ($Q \sim 10\,000$) since surface roughness and finite etching depth are not considered in the calculations. Figures 3(d) and (e) illustrate the calculated spectra for nominal pillar diameters of 5 and 4 μ m (solid lines) and the corresponding experimental results. Again, for the 5 μ m (4 μ m) pillar only a slight correction of the diameter to 5.1 μ m (3.9 μ m) was necessary to achieve agreement with the experimentally observed peak spacing. For decreasing pillar diameter, the whole spectrum shifts to smaller wavelengths and the mode spacing increases. These characteristics are consistent with two well-known principles (see e.g. [15]): (i) the wavelength of the fundamental mode decreases with diameter D; and (ii) the spacing between resonant wavelengths increases monotonically for decreasing diameter (approximately as D^{-2}). In addition to surface roughness, the experimentally observed reduction of the cavity Q factor for decreasing pillar diameter is due to less efficient confinement in the transverse direction which leads to a leaking of the field out of the cavity and subsequently to propagating modes in the plane perpendicular to the main emission direction. Both effects are not included in the generalized transfer-matrix theory [13].

The well-resolved experimental mode structure in figure 3 indicates that the inhomogeneously broadened PL from a large number of QDs in the micropillars supports the displayed modes. For an QD surface density of $\sim 3 \times 10^{10}$ cm⁻² in our sample, the 6 μ m diameter pillar contains ~8500 QDs. We estimate that around 200 QDs spectrally match the fundamental mode. For a given surface density of QDs, the smaller diameter micropillars contain a reduced number of QDs and, hence, a decreasing number of emission lines spectrally match the cavity modes. In addition, the quality factor decreases and the linewidth of the mode broadens. For example, a quality factor of $Q \sim 10\,000$ was measured for the 6 μ m pillar whereas a reduced value of ~8000 was found for a 2 μ m pillar of our sample (not shown).



Figure 4. Photoluminescence spectra from pillars with diameters of (a) $0.6 \,\mu$ m and (b) $0.3 \,\mu$ m performed under pulsed laser excitation. Peak energies are given in eV.

To access individual QD emission, PL measurements were performed on smaller diameter pillars. As an example, typical spectra of 0.6 and 0.3 μ m are illustrated in figure 4. In each case the spectra are dominated by a pair of PL lines which were assigned to excitonic (X) (1.3643 eV 4(a)/1.3651 eV 4(b)) and biexcitonic (XX) emission (1.3614 eV 4(a)/1.3617 eV 4(b)) due to their linear or superlinear dependence on excitation power, respectively. As will be proven in the following, in either case, these line pairs originate from the same single quantum dot. The origin of the PL lines located between X and XX is not known, but could be originated from a charged exciton transition of the same QD or a further excitonic transition from a different QD. Note that it was impossible to resolve the mode structure for the 0.6 and 0.3 μ m pillars even under high optical pumping power densities [6] of $2.3 \,\mathrm{kW} \,\mathrm{cm}^{-2}$ energetically above the GaAs barrier (laser at 1.55 eV). Therefore, the cavity Q factor could not be determined. However, the calculations discussed above verify that with decreasing pillar diameter the mode spacing increases. For example, in a $0.9 \,\mu$ m diameter pillar (not shown) the separation of the fundamental and first-excited transverse mode is 29 nm and the minimum mode spacing of the next higher modes is 3 nm. This suggest that the sharp lines in figures 4(a) and (b) which exhibit a wavelength separation of ~ 2 nm emerge from the same cavity mode. This implies that the estimated Q-factor to be ≤ 450 .

Figure 5 shows the cw laser power dependence of the X (closed triangles) and the XX (squares) intensities from the 0.6 μ m pillar microcavity, and the typical X intensity observed from a QD in a bulk semiconductor (open triangles). Note that under cw laser excitation, the measurements reveal the same excitonic transitions with identical photon energies as were observed using pulsed laser excitation (figure 4(b)). Both X lines show an approximately linear power dependence, whereas the XX line shows a superlinear increase with a slope of 1.7. At high cw excitation powers all lines reveal a saturation behaviour. However, the maximum XX intensity is higher than the X intensity as the exciton state of the dot can capture a second electron–hole pair before the emission of the X photon [16]. An enhancement of the PL intensity by a factor of ~40 was found for X and XX in a pillar microcavity when compared with the PL intensity



Figure 5. Continuous-wave laser power dependence of the X (XX) intensities from a 0.6 μ m diameter QD located in a pillar microcavity X (\blacktriangle), XX (\blacksquare), and in a bulk semiconductor (\bigtriangledown).

of X in a bulk semiconductor. This behaviour could be understood based on two factors: (i) the exciton transition is mainly coupled into the cavity mode by the Purcell effect and/or (ii) the enhanced photon collection effect out of the cavity structure. Signatures of the Purcell effect can be obtained under cw excitation from a comparison of the onset of the PL saturation at high excitation powers of a QD in bulk and a QD in a pillar cavity [17]. This type of analysis relies on the assumptions that the free space exciton lifetime of these QDs is equal and that the pumping rate for the two QDs is the same. The lifetime of the QD in the pillar cavity depends critically on the location of the QD. A near sidewall location could lead to a significant increase in the radiative lifetime [18]. Since we have no information about the location of the QD inside the pillar cavity and cannot exclude slightly different excitation efficiencies, we were not able to determine a reliable estimate of the Purcell factor.

Autocorrelation measurements have been performed to demonstrate single-photon generation under pulsed excitation of QDs in pillar microcavities with different pillar diameters. For instance, figure 6 shows the measured unnormalized correlation function $n(\tau)$ of the fundamental mode of the $6 \,\mu m$ pillar (figure 6(a)) and of the XX QD emission from the $0.3 \,\mu\text{m}$ pillar (figure 6(b)). The corresponding PL spectra are shown in figures 3(c) and 4(b), respectively. The correlation peak areas are related to the conditional probability of detecting a second photon (on the stop) after the first photon has already been detected during the excitation cycle. The measured $n(\tau)$ of both pillars exhibit peaks at integer multiples of the repetition period $T_{rep} = 13.12$ ns, indicating a locking of the photon emission to the pulsed excitation. As expected, for the $6\,\mu m$ pillar diameter all correlation peaks have the same areas which is expected for a Poissonian light source. This is due to the fact that many QDs contribute independently to the mode emission. In contrast with the 6 μ m pillar, the central peak at $\tau = 0$ ns of the 0.3 μ m pillar is significantly suppressed, demonstrating the single-photon nature of the emitted light. However, for a perfect single-photon emitter $g^2(0) = 0$. In our case, $g^2(0) = 0.28$ for the central peak of the 0.3 μ m pillar does not reach its theoretical value of zero. This is caused by the presence of a weak uncorrelated background originating mainly from the wetting layer and leaky modes.

In the following we performed polarization-dependent cross-correlation measurements on the XX-X photon pairs of the 0.6 μ m diameter pillar following the procedure outlined in [19].

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Figure 6. Autocorrelation measurements under pulsed laser excitation obtained from (a) a fundamental mode of 6 μ m diameter pillar (PL spectrum in figure 3(c)) and (b) the XX photon of 0.3 μ m diameter pillar (PL spectrum in figure 4(b)).

The aim of this was to obtain the entire two-photon density matrix and determine the nature of the polarization relationship between these photons by using quantum state tomography. The PL spectrum is shown in figure 4(a). The technique of quantum tomography allows experimental reconstruction of two-photon polarization state density matrices from polarization measurements [20]. Linear polarization analyzers consisting of a $\lambda/2$ waveplate in combination with polarizing beam splitters were used to specify the detected angle of polarization. In addition, a $\lambda/4$ waveplate was used to translate any circular polarization into a linear base of detection. Photon correlation histograms of four selected polarization combinations in pulsed excitation obtained at a power density of 200 W cm⁻² are compiled in figure 7. Two histograms represent linear polarization ($H_{XX}^{start}H_X^{stop} = HH$ and $V_{XX}^{start}H_X^{stop} = VH$) and the other two ($R_{XX}^{start}R_X^{stop} = RR$ and $R_{XX}^{start}L_X^{stop} = RL$) were obtained under circular polarization, respectively. The histograms exhibit a series of peaks, separated by integer multiples of the laser repetition period. Note that counts in the central peaks ($\tau = 0$ ns) occur only if both photons are detected following the same laser pulse, whereas contributions to the histogram side peaks at nonzero time intervals ($\tau = mT_{rep}$, $m = \pm 1, \pm 2, \ldots$) originate from photon pairs detected after different excitation cycles [10]. The zero delay signal is higher than the other peaks, which reflects an enhanced probability of detecting a X photon after a XX photon. Thus, the observed bunching effect clearly indicates the cascaded emission of the XX–X photon pairs. The areas of the central peaks ($\tau = 0$) ns are similar for the selected polarization configurations. This means that in the chosen measurement basis, no polarization correlation exists between the XX and X photons. To obtain the entire information on the polarization in all directions, we measured the complete set of 16 linearly independent states and calculated the two-photon density matrix [19]. The states were measured using the following polarization combinations: HH, HV, VH, VV, RH, RV, DV, DH, DR, DD, RD, HD, VD, VL,



Figure 7. Cross-correlation measurements from a 0.6 μ m diameter pillar of XX (start) and X (stop) photons recorded under pulsed laser excitation at 868 nm for different polarization configurations: (a, b) in linear basis (*HH* and *VH*), (c, d) in circular basis (*RR* and *RL*). Notations are: horizontal *H*, vertical *V*, right circular $R = (H - iV)/\sqrt{2}$, and left circular $L = (H + iV)/\sqrt{2}$.

HL and *RL*, where the first and the second letters refer to the XX and X polarizations, respectively. The polarizations are defined as follows: horizontal *H*, vertical *V*, diagonal $D = (H + V)/\sqrt{2}$, right circular $R = (H - iV)/\sqrt{2}$ and left circular $L = (H + iV)/\sqrt{2}$. Each of the 16 zero delay peak areas was normalized with respect to the total sum of the $\tau = 0$ ns signals obtained from the first four measurements (i.e. *HH*, *HV*, *VH* and *VV*) [19, 20]. We found

$\hat{\rho} =$	0.2621	-0.0043 - 0.0192i	0.0053 - 0.0025i	-0.0175 + 0.0349i	
	-0.0043 + 0.0192i	0.2391	0.0385 - 0.0507i	-0.0172 + 0.0265i	
	0.0053 + 0.0025i	0.0385 + 0.0507i	0.2399	-0.0095 - 0.0160i	
	(-0.0175 - 0.0349i)	-0.0172 - 0.0265i	-0.0095 + 0.0160i	0.2589	

The real part of the normalized two-photon density matrix obtained from the experimental data is shown in figure 8 (left). The on-diagonal components display values of $\rho_{HH,HH} = 0.262$, $\rho_{HV,HV} = 0.239$, $\rho_{VH,VH} = 0.240$ and $\rho_{VV,VV} = 0.259$, whereas the off-diagonal components are extremely small. To understand these results we have calculated the two-photon density matrix for unpolarized light; the graphical representation of this matrix is shown in figure 8 (right). The results are similar to our measured data. Thus, for our investigated sample, almost no polarization correlation between the cascaded XX–X photon pairs was found. Note that a similar observation has already been reported for a single QD inside a microdisk structure [9]. They measured the polarization correlation between XX and X emission was observed. The explanation given was that the spin decoherence for QDs is responsible for the total lack of polarization correlation. In other recent works, signatures of a polarization correlation from single InAs [7, 10] and CdSe [11] QD emission have been reported. Although, in each case, the cross-correlation measurements performed under pulsed excitation revealed a high but non-perfect collinear correlation degree of $\eta \approx 65\%$ (InAs) (derived from data in [7]), $\approx 84\%$ (InAs)

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Figure 8. The real part of two-photon polarization density matrix describing the XX and X photons of $0.6 \,\mu$ m diameter pillar from the experimental data (PL spectrum in figure 4(b)) (left) and the calculated unpolarized state (right) using linear tomography.

(derived from data in [10]), and $\leq 85\%$ (CdSe) [11] between XX and X, respectively, which is due to an asymmetry-induced exciton fine structure. Decoherence effects are expected to originate from carrier and/or phonon scattering processes, thus resulting in a transition [21] from the $(X)_{high} = (+1) - (-1)$ to $(X)_{low} = (+1) + (-1)$ exciton state and vice versa, where (+1) and (-1) are the total electron-hole momentum sub-states of the 'bright' exciton. This would cause a polarization flip of the X photons with respect to the XX decay. The polarization and the fine structure splitting are controlled by the final states of the XX recombination, i.e. the eigenstates of the single exciton [22]. It could also be true in our sample that the lack of polarization correlation between XX and X is related to the spin relaxation of excitons. This implies that the spin relaxation time is significantly shorter than the exciton lifetime, thus cancelling out any initial polarization correlation. Furthermore, slight deviations of the involved excitonic states from 'pure' $(X)_{high}$ and $(X)_{low}$ eigenstates cannot be excluded. In such cases, the superposition of different polarizations should strongly complicate the identification of a significant linear and/or circular polarization correlation. Finally, we cannot exclude polarization destroying light scattering effects inside and in the vicinity of our nano-structured cavity which could contribute to the polarization loss.

4. Conclusion

We have demonstrated the possibility of using the biexciton–exciton radiative cascade of a single QD in a pillar microcavity to efficiently generate triggered photon pairs. Under pulsed excitation, the cross-correlation function of the biexcitonic and excitonic photons show a clear bunching effect due to the cascaded emission of the XX–X photon pairs, whereas no polarization correlations between the biexciton and exciton emission were observed. Due to the enhanced photon collection effect out of the cavity structure an increase in the photoluminescence (PL) intensity by a factor of \sim 40 was found when compared with the corresponding PL intensity in a bulk semiconductor. Furthermore, the light emission from pillar microcavities was investigated within a theory–experiment comparison. Separated narrow mode structures have been well resolved, thus revealing quality factors Q of up to 10000 for larger pillar diameters.

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