Visible single-photon generation from semiconductor quantum dots

Thomas Aichele\textsuperscript{1}, Valéry Zwiller\textsuperscript{2} and Oliver Benson\textsuperscript{1}

\textsuperscript{1} Nano-Optics, Physics Department, Humboldt-Universität zu Berlin, 10117 Berlin, Germany
\textsuperscript{2} Institute of Quantum Electronics, ETH, CH-8093 Zürich, Switzerland
E-mail: thomas.aichele@physik.hu-berlin.de

New Journal of Physics 6 (2004) 90
Received 11 February 2004
Published 29 July 2004
Online at http://www.njp.org/
doi:10.1088/1367-2630/6/1/090

Abstract. In this paper we report recent results on single-photon generation with single InP and CdSe quantum dots. These dots produce single-photons on demand in the visible spectral range 510–690 nm. The emitted photoluminescence was characterized by measuring the autocorrelation function and by performing Fourier spectroscopy on several transitions in the quantum dot. We present the observation and interpretation of carrier trapping and recapture in InP quantum dots which leads to anomalies in the measured correlation functions. Our interpretation is confirmed by numerical simulations based on a rate equation model.

Contents

1. Introduction \hspace{1cm} 2
2. Experiment \hspace{1cm} 2
3. Visible single-photon generation \hspace{1cm} 2
\hspace{1cm} 3.1. InP(GaInP) quantum dots \hspace{1cm} 2
\hspace{1cm} 3.2. CdSe(ZnSe) quantum dots \hspace{1cm} 6
4. Carrier recapture processes in InP quantum dots \hspace{1cm} 8
5. Single-photon Fourier spectroscopy \hspace{1cm} 10
6. Summary \hspace{1cm} 12
Acknowledgments \hspace{1cm} 13
References \hspace{1cm} 13
Efficient generation of single photons is an important task for a variety of quantum optical applications including quantum cryptography [1] and quantum computation [2], but also for fundamental physics. Single-photon sources which rely on single quantum emitters have been demonstrated. Possible systems are molecules [3], diamond NV-defect centres [4, 5] and single atoms [6, 7]. Single semiconductor quantum dots are interesting systems as they cover a wide spectral range, due to the possibility to choose different material systems [8]–[11]. Moreover, they lack blinking and photo-bleaching effects, show a high efficiency and a narrow emission linewidth at low temperature.

In the present study, we report recent results of our experiments using InP [10] and CdSe [11] quantum dots for single-photon generation. The photoluminescence (PL) of single quantum dots was analysed to obtain information about the photon statistics. Spectrometry and Fourier spectrometry provided further information about the spectral properties. Under certain conditions, some quantum dots showed anomalies in the observed single-photon statistics. We explain these effects with carrier trapping and recapture and discuss the results with the help of numerical simulations based on a rate equation model.

2. Experiment

As single-photon sources we have used Stranski–Krastanov-grown InP and CdSe quantum dots in GaInP and ZnSe matrices, respectively. The samples were cooled in a liquid-helium flow cryostat down to 3.6 K. Two step motors integrated in the cryostat allowed the horizontal positioning of the sample. Both the laser excitation and the collection of the PL were performed using a microscope objective with a numerical aperture (NA) of 0.75. This provides a spatial resolution of approximately 500 nm (depending on the PL wavelength). As cw laser source a frequency-doubled Nd:YVO$_4$ laser emitting at 532 nm was used. For pulsed measurements we used a frequency-doubled and mode-locked Ti:sapphire laser emitting 150 fs pulses at 400 nm with a repetition rate of 76 MHz. Imaging through a pinhole isolated a single quantum dot spatially. Spectral filtering was performed by using narrow bandpass filters (between 0.5 and 3 nm FWHM). The PL can then be imaged on a CCD camera and investigated with a grating spectrometer. Time-correlation measurements were performed with a Hanbury Brown and Twiss (HBT) arrangement consisting of two avalanche photodetectors (APDs) and a time interval counting card with a time binning of 37 ps. The time resolution of this system was measured to 800 ps (see figure 1). A schematic of the set-up is shown.

3. Visible single-photon generation

3.1. InP(GaInP) quantum dots

The sample was grown by metal-organic vapour-phase epitaxy (MOVPE) on a GaAs wafer. A GaAs buffer layer was first deposited followed by a 300-nm-thick GaInP layer lattice-matched to GaAs. Nominally, 1.9 monolayers of InP were deposited and the formed dots were overgrown by 100 nm of GaInP. The InP quantum dots in GaInP have been studied at the single dot level [12] and revealed a bimodal size distribution with small dots emitting at around 690 nm, whereas larger
Figure 1. Schematic of the experimental set-up. The inset shows an autocorrelation measurement of a fs-laser pulse that allows us to determine the HBT time resolution.

Figure 2. Photoluminescence spectra taken on a single InP quantum dot. (a) Spectrum over a long-wavelength range. The red line is the detection efficiency of our photodetectors. (b) Sketch of the sample structure. Spectrum (c) was acquired at low and (d) at higher excitation power. X and $X_2$ indicate the exciton and biexciton spectral line, respectively. Spectrum (e) was taken through a narrow bandpass filter.

dots emit at around 750 nm. The measured linewidth (figure 2(a)) of the dot emission under low excitation and low temperature is below 200 $\mu$eV, limited by the resolution of our spectrometer. The density of dots emitting at around 690 nm was estimated to be about $10^8$ cm$^{-2}$ by imaging through a narrow bandpass filter. To increase the light extraction efficiency, a 200-nm-thick Al
layer was deposited on top of the sample to form a mirror. The sample was then glued upside
down with epoxy on to a silicon substrate and the GaAs substrate was removed using a selective
wet etch of H₂O₂/ NH₄OH/H₂O (1 : 1 : 10). Figure 2(b) shows the device structure. Our design has
the potential to obtain an even higher photon emission rate if the mirror is placed at the correct
distance from the emitter: constructive interference of the quantum dot emission with its mirror
image could lead to a shortening of the radiative lifetime [13].

A unique feature of this material system is that the quantum dot emission is centred at
700 nm, where silicon-based single-photon detectors reach their maximum detection efficiency.
This can be up to 70% (PerkinElmer single-photon counting module SPCM-AQR specifications;
see red line in figure 2(a)), which makes InP quantum dots attractive for applications in quantum
technology such as free-space quantum cryptography and optical quantum computing [2].

Figure 2(c) shows the typical PL spectrum of a single quantum dot on this sample.
Because of the low density and the spatial isolation through the pinhole, only few spectral lines
are visible. At low excitation powers one dominant line belonging to the decay of a ground-state
exciton is apparent. If we increase the excitation power, further lines belonging to multi-excitonic
transitions appear, as can be seen in figure 2(d). The assignment of the spectral lines to the different
transitions is done by measuring the excitation power dependency. By using a narrow bandpass
filter with 2 nm FWHM, light resulting from an individual transition can be isolated (figure 2(e)).
The temperature of the sample was 10 K, except when stated otherwise.

To study the photon statistics of such a spectral line, intensity correlations using the HBT
correlator were measured. The temporal distribution of the coincidences of the two APDs is
proportional to the second-order coherence function \( g^{(2)}(\tau) \) as long as the mean time between
the detection events is much larger than \( \tau \). A unique feature of an ideal single-photon source is
the reduction of the correlation function at the time origin to \( g^{(2)}(0) = 0 \). The effect of a reduced
correlation function \( g^{(2)}(\tau) < 1 \) is known as anti-bunching. Figure 3 shows the correlation
function of a single quantum dot under continuous excitation. The grey line in the graph is
Figure 4. Correlation functions of an InP quantum dot obtained under pulsed excitation between 8 and 50 K.

the calculated correlation function of a single emitter by taking into account the limited detector resolution of 800 ps and the extracted decay time constant (2.3 ns). The inset of this figure is a zoom into the region around the origin. The very good agreement between our calculations and the measurement indicates that our sample produces single photons and the value of the dip minimum (5%) is mostly due to the finite time resolution of the correlation set-up. The total photon count rate for this measurement was $1.1 \times 10^4$ counts s$^{-1}$.

Measurements done under pulsed excitation for different sample temperatures are displayed in figure 4. We observe a strong suppression of the peak at $\tau = 0$, which demonstrates the generation of single photons on demand. The total count rate in this measurement was $6 \times 10^4$ counts s$^{-1}$. We can observe single-photon emission, i.e. a correlation peak at time zero below 0.5, up to temperatures of 50 K. Since an $N$-photon state would give a normalized area of $1 - 1/N$, this demonstrates that on average less than two photons per pulse are created and that a single quantum dot was investigated. At higher temperatures the decreasing emission intensity due to thermal escape of the carriers, together with an increased spectral overlap of broadened spectral lines yields poor results. A larger bandgap of the barrier material would allow a higher temperature operation. Antibunching below 0.5 has been observed above 100 K in CdSe quantum dots [14] and above 120 K with InGaAs quantum dots [15].

At higher excitation powers decay from multiple exciton states such as biexcitons and triexcitons (two and three electron–hole pairs, respectively) give rise to additional sharp spectral lines. If spectrally filtered out, light from the biexcitonic or triexcitonic transitions show pronounced anti-bunching as well. In figure 5, correlation measurements under continuous excitation of light from these transitions of another QD are mapped. The biexciton transition (figure 5(a)) has a strong reduction of the coincidences at $\tau = 0$ down to 16% of the maximum level, similar to the data from the exciton decay. Also the correlation function of the triexciton decay (figure 5(b)) clearly exhibits an anti-bunched behaviour. However, here the minimum only reaches a value of 84%. This is because the higher excitation power that is needed to create triexcitons in a QD causes additional spectral lines that spectrally overlap with the filtered line. A simultaneous use of single photons from the different spectral lines could be of use in quantum optical applications, e.g. to enhance the effective transition rate in a quantum cryptography procedure [16].

New Journal of Physics 6 (2004) 90 (http://www.njp.org/)
3.2. CdSe(ZnSe) quantum dots

This sample was grown by molecular-beam epitaxy (MBE). A 1-μm-thick ZnSe buffer layer was deposited at 310 ˚C and was followed by three monolayers of CdSe deposited at a temperature of 230 ˚C. Following a growth interrupt of 15 min at 230 ˚C and a 40-min annealing at 310 ˚C, the dots were overgrown by 85 nm of ZnSe [17]. Previous studies by atomic force microscopy and transmission electron microscopy revealed the shape and the sizes of these dots with heights of 1.6 nm and base lengths shorter than 10 nm [18]. Atomic force microscopy studies of similar samples revealed a dot density of 10^{11} cm^{-2}, implying that the average dot spacing is smaller than our set-up resolution (500 nm). The overall PL from an ensemble of quantum dots shows an inhomogeneously broadened spectral band centred around 510 nm with a width of 15 nm [19]. To perform single-quantum-dot spectroscopy, mesas with lateral extensions of 100 nm were prepared by electron-beam lithography and wet-chemical etching. In this case, PL spectra consist of single narrow lines, which correspond to electron–hole recombination from single quantum dots [19, 20]. The samples are naturally n-type doped [21]. As a result, donor electrons may be captured by the quantum dots and together with optically excited electron–hole pairs form negatively charged excitons (trions). Both charged and neutral dots have been studied previously by performing spectroscopy at the single dot level [19, 22]. Single-photon emission with single CdSe quantum dots have also been reported in [14].

The lifetime of the transitions is typically of the order of 300 ps [20], which is shorter than for III–V quantum dots. This fact allows single-photon emission with a higher time accuracy and a possibly higher rate than with InP quantum dots. In contrast with II–VI colloidal nanocrystals no blinking was observed down to timescales of 10 ms. Figure 6 shows a spectrum taken on a single mesa containing only few dots. The lines of interest are labelled as $X^-$ (charged exciton) and $X_2^-$ (charged biexciton). The assignment of the lines to these states was done by observing the excitation power dependency of the lines, where $X^-$ shows a linear and $X_2^-$ a quadratic behaviour (figure 6(a) and its inset). Previous studies [22] revealed that the energy spacing of charged quantum dots is typically 6 meV, whereas the line spacing of uncharged dots is approximately 20 meV. Figure 6(b) shows a spectrum taken without any filter (bottom curve) and with two filters (top curve). The narrower of the two filters had a transmission of 3 nm FWHM (see transmission
Figure 6. Spectra taken on a single mesa on the CdSe sample. (a) Spectra at different excitation powers. The inset gives the intensity versus excitation power of the two spectral lines labelled as $X^-$ and $X^{-2}$. The solid and dashed curves are the linear and quadratic fits, respectively. (b) Spectrum under the experimental conditions of the correlation measurements in figure 7. The upper graph is the filtered spectrum and the bottom graph the unfiltered spectrum. In these figures offsets were added for clarity.

Figure 7. Autocorrelation measurement of a charged exciton transition of a CdSe quantum dot. The numbers are the peak areas normalized to the average area of the higher-order peaks.

curve in figure 6(b)) and was tilted so that its maximum transmission fitted to the observed spectral line $X^-$. In figure 7, the results of the correlation measurements on the filtered line $X^-$ is plotted. The total count rate was $2.8 \times 10^4$ counts s$^{-1}$ and the integration time was 2100 s. The area under the peak at $\tau = 0$ reached 28% of the average area of the peaks at higher times. We attribute the somewhat high area of this central peak to the pollution of the filtered charged exciton emission by the emission of the charged biexciton and other close lines.
Figure 8. Correlation measurements on three different dots on the InP quantum dot sample as described in the text. The sample temperatures were 15 K for measurement (a) and 8 K for measurements (b) and (c). The three graphs were obtained under pulsed excitation.

Because of the short decay time of the exciton state, the width of the correlation peaks of 800 ps is given by the time resolution of the HBT set-up. This implies that single-photons could be generated on demand up to a rate of the order of 1 GHz. In our experiments, the emission rate was limited by the fixed repetition rate of the excitation laser. Moreover, the limited collection efficiency further reduces the effective detection rate. Still we observe reduced central correlation peaks below 0.5 up to count rates of $10^5 \text{s}^{-1}$. At higher excitation powers even more spectral lines appear and further disturb the single-photon emission.

Similar correlation functions are measured again up to a temperature of 40 K, whereas the normalized area of the $\tau = 0$ peak increases up to 0.4. At higher temperatures, the number of emitted photons decreases drastically deteriorating the signal-to-noise ratio in the same manner as with the InP dots.

4. Carrier recapture processes in InP quantum dots

In this section, we discuss an anomaly that was observed in pulsed autocorrelation measurements on the PL of some dots in the InP quantum dot sample. In figure 8, we have displayed measurements on three dots, where this effect is differently pronounced. The measurements were performed on different dots in the sample. The excitation light source was a 150-fs pulsed laser light at 400 nm. The temperature ranged between 8 and 15 K. Figure 8(a) shows similar correlation data as in figure 4. The measurement shows clear antibunching, with a minimum at $\tau = 0$, which indicates that due to the spectral and spatial filtering process only a single quantum dot transition is observed. However, within the order of 1 ns, long before the next excitation laser pulse impinges, there is a slight increase (bunching) of correlations. Also a pronounced offset of the measured correlation is observed. Figure 8(b) shows a dot on which this effect is even more pronounced with a higher bunching time scale (2.5 ns). The higher order peaks become relatively broad and start to overlap, which creates an even higher offset in the correlation function. However, this is not due to unwanted background light, as the coincidences significantly drop below this offset at $\tau = 0$. We have also observed the very extreme case
where the peak broadening is strong enough to completely wash out the correlation peaks. This can be seen in figure 8(c). Still there is a strong reduction of the coincidences at time zero. In these measurements, the proper mode-locking of the pulsed laser was carefully checked. These observations are not unique and occur in a similar way on a multitude of dots on this sample. We attribute this effect to a re-excitation process that takes place in the quantum dot sample: the optical excitation above the barrier band gap creates a large number of electrons and holes in the conduction and valence band, respectively. These electrons and holes can be captured in the quantum dot and relax into the excited ground states, where they can perform the exciton transitions that are investigated. However, they may also be captured for a certain time in charge traps in the barrier material, close to the quantum dot. The presence of efficient traps in this quantum dot sample may be related to the MOVPE growth process, compared with MBE growth that is mostly used for the growth of InAs dots. An additional signature of the presence of charge traps is the relatively large linewidth of the quantum dots (see the next section). After the initially excited exciton decayed, further electrons and holes diffuse from the potential traps into the dot and thus populate it again.

To gain further insight into the recapture process, we have taken correlation measurements on the same single dot, but for increasing pump power. The results are shown in figure 9(a). A typical feature of all measurements is the suppression of correlations at $\tau = 0$. However, for increasing pump power a bunching shoulder starts to grow close to the central minimum. This feature around $\tau \approx 0$ is very similar to a cw measurement, with the difference that the excitation rate is not constant but exponentially decaying, as described in the next paragraph. With increasing excitation power the time constant of the anti-bunching dip decreases. Thus, in the last measurement, the narrow antibunching dip at $\tau = 0$ is completely washed out due to the finite time resolution of our measurement set-up.

Figure 9. (a) Correlation measurements on a single dot for different excitation intensities. The black and red lines are the measured and simulated correlations, respectively. The numbers are the laser excitation powers for these specific measurements under a wide-field illumination. (b) The re-excitation time scales $t_{\text{reexc}}$ that are obtained from the simulations versus the excitation power.
For a further study, we have performed Monte Carlo simulations that are based on the model proposed in [23]: a quantum dot can be excited by capturing electron–hole pairs to the exciton, biexciton, etc. state. When excited above the band gap, single charges (electron or holes) can also be captured and change the charging of dots. In contrast with the excitation, the decay process of (multi-)excitons does not change the dots charging as it is a recombination process of one electron and one hole. In our simulations, we have extended this model by a re-excitation process that is caused by additional charges that are trapped for some time in the barrier material. Therefore, we assume that the charge capture rate $p_{\text{capt}}(t)$ is proportional to the number of charges and decays exponentially with time. Thus $p_{\text{capt}}(t) = p_{\text{capt}}(0) \exp(-t/t_{\text{reexc}})$. Here $t_{\text{reexc}}$ is the time scale on which re-excitation occurs. The red lines in figure 9 show the simulated correlation functions. In these simulations, the probability to capture electron–hole pairs was kept proportional to the excitation power of the measured data. An additional offset was added to the simulated data to fit the measured curve. The simulations agree very well with the measured results. From these simulations we estimated the re-excitation rate to be proportional to the excitation power with a proportionality constant of $p_{\text{capt}}(0) \approx 0.4 \, \text{GHz} \, \text{nW}^{-1} \, \mu\text{m}^{-2}$, whereas the exciton decay rate was 2 GHz. The re-excitation time $t_{\text{reexc}}$ was found to depend strongly on the excitation intensity and varies between 1 and 6 ns (figure 9(b)).

The described re-excitation process does not alter the anti-bunched nature of the emitted light field, because still only one photon is emitted at a time and thus the correlation function drops below 1 at $\tau = 0$. However, it is an obstacle in the way towards single-photon generation on demand, as it prevents the quantum dots to emit only one photon per excitation pulse. In many single-photon applications, the photon emission needs to be strictly correlated to a trigger pulse, such as an optical or electronic excitation pulse, whereas photons outside the time window given by this trigger pulse need to be strongly suppressed.

5. Single-photon Fourier spectroscopy

So far only the second-order coherence function of the emitted light was observed, which is an important property for quantum cryptography applications. However, other applications, such as linear optical quantum computation [2] have additional requirements on the single-photon quantum bits. To process the photons in optical quantum gates, a Fourier-limited linewidth is a necessary property. Linewidth measurements on single quantum dots have been performed using high-resolution spectroscopy [24], four wave mixing [25] and coherent spectroscopy in the time domain [26]. In contrast with this, Fourier spectroscopy [8, 27] combines a high resolution with a robust set-up and low photon losses. In this section, we report on linewidth measurements of the InP quantum dot sample using Fourier spectroscopy with a Michelson interferometer. Measurements were performed on both the excitonic and biexcitonic spectral lines. More extensive measurements and analysis will be published elsewhere [27].

The Michelson interferometer consisted of a fixed mirror and a mirror mounted on a piezo-translator with an 80 µm range and a step motor with 5 mm range. The interference signal is detected with a CCD camera. The integration time on the camera was set to 500 ms. Imaging on a CCD array instead of a single photodiode makes it possible to investigate several dots simultaneously. Data acquisition is performed by setting the step motor on a fixed position and scanning the piezo over a distance of several wavelengths. The images and the film in figure 10 show the time evolution of a CCD view while moving the piezo-mounted mirror.
There are several quantum dots visible that slowly change between constructive and destructive interferences. Figure 10(a) shows the intensity of the marked quantum dot versus the mirror position.

To avoid intensity fluctuations a normalized measure for the contrast of the interference fringes was used, the visibility \( v = (I_{\text{max}} - I_{\text{min}})/(I_{\text{max}} + I_{\text{min}}) \), where \( I_{\text{max}} \) and \( I_{\text{min}} \) are the maximum and minimum interference intensities at a fixed step motor position. For example, the visibility of the graph in figure 10 is 77%. By probing the visibility at different coarse positions of the mirror we can obtain information about the Fourier transform of the optical spectrum, as can be seen in figure 11. Here (a) and (b) give the visibility of a filtered exciton and biexciton lines, respectively. Autocorrelation measurements on these lines demonstrated single-photons emission. Due to the filtering, the incoherent background of the observed Fourier spectrum consists partially of the spectral line itself and the filter transmission. This fact gives rise to a bend in the measured graph. The fits in these figures correspond to the sum of a Gaussian and exponential functions as a model for the Gaussian and Lorentzian spectral lineshapes of the filter transmission and spectral line, respectively. A comparison with a measurement of a white light source filtered by the bandpass filter (coherence length 0.4 mm) overlaps with the short time scale of the graphs in figure 11. The long-scale behaviour however suggests Lorentzian lineshapes. The coherence lengths of the fits are 2.9 and 4.1 mm for the exciton and biexciton lines, respectively. This accounts for linewidths (FWHM) of 130 and 95 \( \mu \text{eV} \), respectively. We have also observed even narrower linewidths down to 110 and 50 \( \mu \text{eV} \) for the exciton and biexciton, respectively [27]. The narrower biexciton linewidth is a repeatedly observed feature on this sample.

Measurements of the radiative lifetime on these quantum dots gave a value of 1.2 ns. This corresponds to a homogeneous spectral linewidth of 0.5 \( \mu \text{eV} \). This is two orders of magnitude narrower than the inhomogeneous linewidth measured by Fourier spectroscopy. It has been speculated that the linewidth broadening in InP dots is due to charging effects and fluctuating...
Figure 11. The visibility of the interference fringes versus the Michelson path difference for (a) the exciton and (b) the biexciton spectral line. The fits are combined Gaussian and exponential fits as described in the text.

6. Summary

In this paper, we have reported on single-photon generation with single quantum dots in the visible regime. InP quantum dots were used to produce single photons around 700 nm. At this wavelength, highest detection efficiencies with Si-based photo detectors are currently available, which makes InP quantum dots preferable for free-space quantum optical applications. We have demonstrated single-photon statistics from various transitions from multi-excitonic states including biexciton and triexciton decays. Multi-photon generation from single quantum dots may find application in quantum cryptography devices, since a higher rate of photons also enhances the maximum transmission rate of the quantum information. Fourier spectroscopy, which reveals information about the spectral linewidth and lineshape was performed as well. Single photons with a lower emission wavelength (510 nm) have been generated with CdSe
quantum dots. This system offers a shorter lifetime and makes higher bandwidth single-photon generation possible.

The effect of carrier recapture from charge traps which leads to a non-radiative re-excitation of some quantum dots in the InP quantum dot sample was studied. In the extreme case, this effect can even lead to a quasi-continuous (but still antibunched) emission of photons under pulsed excitation. We have described and analysed this effect and compared the results with numerical simulations.

Acknowledgments

We thank W Seifert at Lund University for providing the InP quantum dot sample and F Henneberger at Humboldt University Berlin for providing the CdSe quantum dot sample. This work was supported by the Deutsche Forschungsgemeinschaft (DFG grant no. BE2224/11). VZ acknowledges funding from the European Union’s Marie Curie fellowship.

References

[1] Gisin N, Ribordy G, Tittel W and Zbinden H 2002 Rev. Mod. Phys. 74 145
[2] Knill E, Laflamme R and Milburn G J 2001 Nature 409 46
[3] Lounis B and Moerner W E 2000 Nature 407 491
[4] Kursiefer C, Mayer S, Zarda P and Weinfurter H 2000 Phys. Rev. Lett. 85 290
[5] Brouri R, Beveratos A, Poizat J-P and Grangier P 2000 Opt. Lett. 25 1294
[6] Kuhn A, Hennrich M and Rempe G 2002 Phys. Rev. Lett. 89 067901
[7] McKeever J, Boca A, Boozer A D, Buck J R and Kimble H J 2003 Nature 425 268
[8] Santori C, Fattal D, Vučković J, Solomon G and Yamamoto Y 2002 Nature 419 594
[9] Michler P, Kiraz A, Becher C, Schoenfeld W V, Petroff P M, Zhang L D, Hu E and İmamoğlu A 2000 Science 290 2282
[10] Zwiller V, Aichele T, Seifert W, Persson J and Benson O 2003 Appl. Phys. Lett. 82 1509
[11] Aichele T, Zwiller V, Benson O, Akimov I and Henneberger F 2003 J. Opt. Soc. Am. B 20 2189
[12] Persson J, Holm M, Pryor C, Hessmann D, Seifert W, Samuelson L and Pistol M-E 2003 Phys. Rev. B 67 035320
[13] Bourdon G, Robert I, Adams R, Nelep K, Sagnes I, Moison K M and Abram I 2000 Appl. Phys. Lett. 77 1345
[14] Sebald K, Michler P, Passow T, Hommel D, Bacher G and Forchel A 2000 Appl. Phys. Lett. 81 2920
[15] Mirin R P 2004 Appl. Phys. Lett. 84 1260
[16] Aichele T, Reinaudi G and Benson O 2004 submitted
[17] Rabe M, Lowisch M and Henneberger F 1998 J. Crystal Growth 184/185 248
[18] Litvinov D, Rosenauer A, Gerthsen D, Kratzert P, Rabe M and Henneberger F 2002 Appl. Phys. Lett. 81 640
[19] Lowisch M, Rabe M, Kreller F and Henneberger F 1999 Appl. Phys. Lett. 74 2489
[20] Flissikowski T, Hundt A, Lowisch M, Rab M and Henneberger F 2001 Phys. Rev. Lett. 86 3172
[21] Yao T 1985 J. Crystal Growth 72 31
[22] Akimov I A, Hundt A, Flissikowski T and Henneberger F 2002 Appl. Phys. Lett. 81 4730
[23] Santori C, Fattal D, Vučković J, Solomon G S, Waks E and Yamamoto Y 2003 Preprint condmat/0308323 v1
[24] Bayer M and Forchel A 2002 Phys. Rev. B 65 041308
[25] Borri P, Langbein W, Schneider S, Woggon U, Sellin R L, Ouyang D and Bimberg D 2001 Phys. Rev. Lett. 87 157401
[26] Toda Y, Sugimoto T, Nishioka M and Arakawa Y 2000 Appl. Phys. Lett. 76 3887
[27] Zwiller V, Aichele T and Benson O 2004 Phys. Rev. B 69165307
[28] Blome P G, Wenderoth M, Hubner M, Ulbrich R G, Porsche J and Scholz F 2000 Phys. Rev. B 61 8382

New Journal of Physics 6 (2004) 90 (http://www.njp.org/)