Smooth transition into stimulated emission of InP quantum dots based high-Q microdisk cavities

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Abstract. We report on optical investigations of InP quantum dots embedded in a wet-etched GaInP microdisk cavity. The structures exhibit modes with quality factors on the order of $10^4$. A combination of consistent power-dependent measurements of the optical power output, the $2^{nd}$-order autocorrelation function $g^{(2)}(\tau)$ and the emission linewidth give proof for high-$\beta$-lasing. The results correspond very well to those obtained from micropillar cavity lasers.

1. Introduction

Significant progress in the fabrication of semiconductor micro-resonator structures have lead to a plentitude of different realizations of high quality quantum emitter devices which exhibit stimulated emission. Alongside micropillars and photonic crystal resonators, whispering-gallery-mode (WGM) microdisk resonators have proven to be suitable candidates for the cavities of such devices, due to their high $Q$-factors and relatively small mode volumes. These characteristics allow for high $\beta$-values [1], i.e. a high spontaneous emission coupling factor of the lasing mode, and thus provide the possibility of approaching so-called zero-threshold lasing [2].

WGM lasers containing quantum dots (QD) as the lasing medium have been presented for a variety of material systems covering a wide range of emission wavelengths. Among these, the most thoroughly investigated systems consist of InAs or (In$_x$Ga$_{1-x}$)As QDs embedded in GaAs or (Al$_x$Ga$_{1-x}$)As microdisks providing emission in the 900 to 1300 nm range and exhibiting WGMs with $Q$-factors of up to $10^5$ [3, 4, 5]. The upper and lower bounds of the wavelength range is marked by Ge QDs in Si- (1200 - 1600 nm) and CdSe QDs in ZnSe-microdisks (~520 nm), respectively [6, 7]. Very recently, InP QDs embedded in GaInP waveguide microdisks ($Q \sim 2 - 5 \times 10^5$) have been reported to show lasing at ~ 750 nm [8]. It is now intuitive to investigate the photon statistics fluctuations of phosphidic micro-resonator lasers (as performed for InAs/GaAs based micro-resonator lasers [9]) to get a deeper insight in the nature of the lasing transition in theses systems.

In this paper we report lasing in the spectral region between 660 and 675 nm from InP QDs embedded in a wet-etched freestanding GaInP microdisk exhibiting $Q$-factors of up to $1.5 \times 10^4$. This wavelength is in the regime of the highest sensitivity of widely used Si photodiodes. We paid particular attention to the regime of the onset of stimulated emission where both a rapid drop of
the linewidth and a gradient of the second-order correlation function from values well above one (photon-bunching) towards unity (Poissonian statistics, characteristic for laser emission) was revealed. This is in good accordance with examinations of the lasing transition of InAs QDs in GaAs micropillar cavities [9].

2. Sample preparation and experimental setup

Sample growth was performed on a (100) silicon doped GaAs substrate miscut by 6° toward the [111] buffer direction. Using metal-organic vapor-phase epitaxy (MOVPE), the growth process started with a 100 nm GaAs layer followed by a short-period superlattice. Subsequently, 1 µm of Al$_{0.5}$Ga$_{0.5}$As was deposited as an sacrificial layer for the arsenic selective wet etching process. Finally, a AlGaInP/GaInP layer system with a thickness of 200 nm including InP QDs embedded in a separate confinement heterostructure was grown. Further details on the growth process of the QDs can be found in Ref. [10]. In the first step of the microdisk structuring, lithographic processing of disk patterns with diameters of 5 µm and 10 µm was performed. After smoothing the patterns during a 90 s resist reflow process they were etched through the post material using a hydrobromic acid isotropic wet etch. The resulting pillar structures had a nominal diameter of 4 µm and 9 µm. The removal of the resist and the underetching of the disk material was performed using AZ300T resist stripper. This crystallographic etching step provided a selective etching of the arsenic post material and yielded high quality disk structures, an example of which is displayed in Figure 1(a).

![Image](image-url)

**Figure 1.** (a) Scanning electron microscopy image of a 9 µm-diameter microdisk structure. (b) µPL spectrum obtained from a 4 µm-diameter microdisk at low excitation power density (∼ 10 W/cm$^2$). (c) Corresponding high excitation power density (∼ 250 W/cm$^2$) spectrum. The pump powers $P_{av}$ are to be interpreted as time-averaged mean pump powers.

All optical investigations were performed with the sample mounted in a helium-flow cryostat (∼ 5 K) which is attached to two stepper motors to achieve a 2D lateral scanning capability with a resolution of ∼ 100 nm. We used a confocal microscope setup including a 50× objective and a 80:20 beamsplitter to both focus the incident excitation laser beam to a spot diameter of ∼ 1.5 µm and collect the PL from the microdisks. The sample was excited by laser pulses at 600 nm ($\Delta\lambda \sim 2$ nm) with a temporal width of 4 ps full width at half maximum (FWHM) at a repetition rate of 50 MHz. The collected micro-photoluminescence (µPL) was dispersed by a 500 mm monochromator and detected by a charged-coupled device (spectral resolution 110 µeV). For $g^{(2)}(\tau)$ 2nd order photon-correlation measurements a Hanbury-Brown and Twiss (HBT) setup was used providing a temporal resolution of 350 ps. As we use pulsed excitation, the pump power is denoted in terms of an time-averaged mean pump power $P_{av}$ in the following.
3. Results of the optical investigations

We performed basic investigations concerning the modes and the Q-factor of the cavity in terms of µPL measurements at different excitation powers. In Fig. 1 (b) and (c) we present corresponding emission spectra from a 4 µm-diameter microdisk for the conditions of low and a high excitation power densities, respectively. For low excitation power we observe several distinct lines, which are assigned to WGMs, on top of the spectrally broadened QD ensemble. For an excitation power density well above the lasing transition (discussed below) we observe emission mainly through a dominant mode (labeled Mode A) at 662 nm and a somewhat weaker mode at 665 nm. Furthermore, various smaller modes which do not exhibit lasing contribute to the spectrum. To determine the quality factor of mode A we tracked the power dependence of the mode’s spectral linewidth. Approaching transparency close to the lasing threshold, where absorption losses become negligible, Q can be approximated as $Q = E/\Delta E = 10000 \pm 300$, where $\Delta E$ corresponds to the FWHM of the mode.

![Figure 2](image-url)

**Figure 2.** Investigation of the transition regime between dominantly spontaneous and stimulated emission of a single mode of a 4 µm-diameter microdisk. (a) Optical output in double-logarithmic scale. (b) Evolution of $g^{(2)}(\tau=0)$. (c) The linewidth obtained from a fit to the PL data. The red dotted line indicates the resolution limit of the PL setup. Please note, that the mode under investigation is not the mode labeled ”Mode A” in Fig. 1(c) but the mode displayed in the inset of subfigure (a).

In Fig. 2 the results of a detailed examination of the transition regime between dominantly spontaneous and dominantly stimulated emission (highlighted by the grey shaded area) is displayed. At this, a detailed µPL power series (a), a power-dependent series of HBT autocorrelations (b) and a determination of the mode’s linewidth (c) are plotted on a logarithmic pump power scale. Please note, that these measurements were not performed on the mode labeled ”Mode A” in fig. 1 but on a different mode of a 4µm-diameter microdisk with an emission wavelength of 672 nm. In the µPL power series presented as a double-logarithmic I/O-graph one can perceive a smooth s-shaped intensity transition characteristic for small mode volume semiconductor microcavity lasers [9]. The small offset between the two regimes, i.e. well below and above the transition region, of less than an order of magnitude also suggests a high $\beta$-value well above conventional lasers with $\beta \sim 10^{-5}$ typically. Fig. 2(b) displays Poisson-normalized values of $g^{(2)}(\tau = 0)$ as extracted from a series of pulsed power-dependent HBT autocorrelation measurements by integrating over the zero delay peak. For these measurements
the $\mu$PL was spectrally pre-filtered to a bandwidth of approximately 0.6 nm (1.6 meV) to only correlate signal originating from the mode under investigation. At $P_{av} \sim 2 \mu W$, in the region identified as the onset of lasing by the superlinear increase in the I/O-graph, one clearly observes a signal of photon bunching ($g^{(2)}(\tau = 0) > 1$). For higher pump powers the values of $g^{(2)}(\tau = 0)$ approach unity as expected for stabilized laser emission. This result corresponds very well to measurements performed on QD-fed lasing modes in micropillar cavities [9]. Below the transition region $g^{(2)}(\tau = 0)$ exhibits values close to one in contrast to the expected thermal behavior of spontaneously emitting QDs. We accredit this observation to the limited temporal resolution of our HBT setup. Finally, in Fig. 2(c) the power-dependence of the mode’s linewidth is investigated. The plotted values are obtained from a Gaussian fit to the PL data. As the apparatus function of our detection setup becomes innegligible at the resolution limit, a Gaussian fit yielded the best results. In the grey shaded area highlighting the onset of stimulated emission the linewidth substantially decreases. We explain this narrowing in accordance with Schawlow and Townes[11] who predicted a reciprocally proportional dependence of the lasing modes linewidth from its optical power output $\Delta E \sim 1/P_0$. Thus, the superlinear increase of the optical power output in the transition region between dominantly spontaneous and dominantly stimulated emission is accompanied by a decrease of the emission’s spectral bandwidth as a characteristic fingerprint of the onset of lasing. As marked in Fig. 2(c) the linewidth decreases to values below the spectral resolution of our setup.

4. Conclusion
In summary, we presented high quality microdisk structures manufactured using a combination of MOVPE growth and a refined wet etching technique. The onset of lasing was shown and explicitly investigated by a combination of consistent power-dependent I/O-, HBT autocorrelation and linewidth measurements. Future perspectives of this work are the controlled coupling of individual QDs to microdisk modes and studies on coupling between QDs in different microdisks.

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References
[1] Slusher R E, Levi A F J, Mohideen U, McCall S L, Pearton S J and Logan R A 1993 Appl. Phys. Lett. 63 1310.
[2] De Martini F and Jacobovitz G R 1988 Phys. Rev. Lett. 60 1711.
[3] Cao H, Xu J Y, Xiang W H, Ma Y, Chang S-H, Ho S T and Solomon G S 2000 Appl. Phys. Lett. 76 3519.
[4] Michler P, Kiraz A, Zhang L, Becher C, Hu E and Imamoglu A 2000 Appl. Phys. Lett. 77 184.
[5] Srinivasan K, Borselli M, Painter O, Stintz A, and Krishna S 2006 Opt. Express 14(3) 1094.
[6] Xia J S, Nemoto K, Iegami Y, Shiraki Y and Usami N 2007 Appl. Phys. Lett. 91 011104.
[7] Renner J, Worschech L, Forchel A, Mahapatra S, Brunner K 2006 Appl. Phys. Lett. 89 231104.
[8] Chu Y, Minatirov A M, He Y, Merz J L, Kalyuzhnyy N A, Lantratov V M and Mintairov S A 2009 Phys. Lett. A 373 1185.
[9] Ulrich S M, Gies C, Ates S, Wiersg J, Reitzenstein S, Hofmann C, Löffler A, Forchel A, Jahnke F and Michler P 2007 Phys. Rev. Lett. 98 043906.
[10] Schulz W M, Roßbach R, Reischle M, Geirne G J, Bommer M, Jetter M abd Michler P 2009 Phys. Rev. B 79 035329.
[11] Schawlow A and Townes C 1958 Phys. Rev. 112 1940.