Low threshold and room-temperature lasing of electrically pumped red-emitting InP/(Al$_{0.20}$Ga$_{0.80}$)$_{0.51}$In$_{0.49}$P quantum dots

Marcus Eichfelder, Wolfgang-Michael Schulz, Matthias Reischle, Michael Wiesner, Robert Roßbach, Michael Jetter and Peter Michler

Institut für Halbleiteroptik und Funktionelle Grenzflächen, Universität Stuttgart, Allmandring 3, 70569 Stuttgart, Germany

E-mail: m.eichfelder@ihfg.uni-stuttgart.de

Abstract. In this letter, we report on laser light emission in the red spectral range. Self-assembled InP quantum dots being electrically pumped were embedded in a microcavity mesa realized by monolithically grown high-reflectivity AlGaAs distributed Bragg reflectors. Common semiconductor laser processing steps were used to fabricate stand-alone index-guided vertical-cavity surface-emitting lasers with oxide apertures for optical transverse mode confinement and electrical current constriction. Ultra-low threshold current densities of around 10 A/cm$^2$ and room temperature lasing were achieved.

1. Introduction

Highly efficient solid-state emitters have proven to be very attractive light sources. Beyond microdisk structures [1] and photonic-crystal microcavities, vertical-cavity surface-emitting lasers (VCSEL) [2] provide ultralow threshold operation even in the sub-milliampere regime [3] and high-speed modulation capability [4]. Additionally, the easy coupling to optical fibers and on-wafer processing are attractive features. Furthermore, for such a laser device with low threshold current, it is essential to decrease the pumped mode volume by using an oxide aperture above the cavity [5]. By using zero-dimensional quantum dots (QDs) as the active medium of semiconductor lasers, theory has predicted splendid properties compared to higher dimensional media [6-8], such as low thresholds and broader gain spectra. In Ref. [3], the authors showed low threshold current densities of around 113 A/cm$^2$ for micropillar lasers in the InGaAs/GaAs material system with a QD density of $5\times10^9$ cm$^{-2}$. World record transparency current density value of 6 A/cm$^2$ for one QD layer with a QD density of $1\times10^{11}$ cm$^{-2}$ in the InGaAs/GaAs material system was reached by the authors in Ref. [9]. It is also preferable to fabricate QDs at shorter wavelengths as active emitters for on-board optical interconnects and polymer optical fiber (POF) applications as common avalanche photo diodes have their highest photon detection efficiency in the red spectral range. In addition, data communication via POF desires wavelengths around 650 nm which is easily reachable using InP/AlGaInP QDs.
2. Sample fabrication

The sample structure was fabricated by metal-organic vapor-phase epitaxy (MOVPE) with standard precursors at low pressure (100 mbar) on (100) GaAs substrates oriented 6° toward the [111]A direction. The bottom distributed Bragg reflector (DBR) consists of 45 λ/4-pairs of Al$_{0.50}$GaAs/AlAs grown at 750°C. The single-layer of self-assembled InP-QDs was grown using the Stranks-Krstanow growth mode [10] by depositing 2.31 monolayers (ML) of InP at 650°C and a growth rate of 1.05 ML/s. The QDs were fabricated on (Al$_{0.20}$Ga$_{0.80}$)$_{0.51}$In$_{0.49}$P as barrier material in the center of a one wavelength-thick (Al$_{0.55}$Ga$_{0.45}$)$_{0.51}$In$_{0.49}$P cavity spacer which is lattice-matched to GaAs [11]. The growth was interrupted for 20 s directly after the deposition of the QDs in order to ripen the QDs. Atomic force microscope measurements were used to determine the surface density of the QDs ($5.5 \times 10^{10}$ cm$^{-2}$). To form a current aperture for electrical pumping of the QDs, an Al$_{0.98}$GaAs oxidation layer was inserted above the cavity. The oxide aperture leads to a number of quantum dots of $5 \cdot 10^3$ to $1 \cdot 10^5$ lying spatially under the respective aperture opening. Later on, the investigated VCSELs are labelled according to their size of oxide aperture diameter as follows: VCSEL 1 (15.7 µm) and VCSEL 2 ($2 \times 5.7$ µm, minor and major axis of the elliptical aperture). A top DBR consisting of 36 λ/4-pairs of Al$_{0.50}$GaAs/Al$_{0.95}$GaAs with linearly graded interfaces grown at 750°C finalized the microcavity. The cavity was designed to have a normal-incidence cavity resonance at around 1.9 eV at room temperature (RT). The mesa microcavity was also investigated using a scanning electron microscope (SEM) (Fig. 1 (a)). A scheme of the device layout is shown in Fig. 1 (b).

3. Electroluminescence measurements

Temperature-dependent electroluminescence (EL) experiments were performed using a He-flow cryostat which enables temperatures between 4-300 K. A direct current (dc) power source was used as the electric pump source. The EL was collected with a 50× microscope objective (NA 0.45), dispersed using a 0.75 m spectrometer and detected using a charge-coupled-device camera. The RT (290 K) overview spectrum in Fig. 2 (a) shows the laser emission line due to the cavity resonance positioned at 1.9 eV for VCSEL 1 which is blue detuned with respect to the QD ensemble. A high spectral resolution EL measurement of the above mentioned sharp laser line reveals a large number of higher transverse modes on the high energy side of the fundamental mode as shown in Fig. 2 (b). As the aperture diameter is reduced, the high resolution measurements reveal a smaller number of higher transverse modes (Fig. 2 (c)). In addition, the splitting between the modes is increased in comparison to VCSEL 1. The quality factor $Q$ of the cavity can be determined from the linewidth $\Delta E$ of the fundamental mode at transparency yielding a value of $Q = \frac{\Delta E}{E} = 4500$. A further reduction of the aperture diameter to an elliptically shaped 2×5.7 µm aperture displays the general indication that the number of transverse modes is further decreased and the mode splitting between the fundamental mode and higher order modes is enhanced. In fact, these two effects are known from micropillar lasers for different pillar diameters [12,13]. We did not observe an obvious mode splitting from the laser with the elliptically shaped oxide aperture as one would expect [14]. This might be due to increased scattering losses [15] affecting the mode component associated with the minor axis of the elliptically shaped oxide aperture. On the other hand, the absence of mode splitting could...
Figure 2. (a) Overview spectrum of VCSEL 1 showing lasing action at a drive current of 2.12 kA/cm$^2$ at RT. (b) and (c) High spectral resolution electroluminescence measurements of VCSEL 1 and 2. The different peak position in energy for each laser is mainly due to different positions on the wafer.

also be attributed to an asymmetric current flow due to the misoriented substrate [16]. We expect the mode spacing to be dominated by the large axis of the oxide aperture of VCSEL 2.

4. Performance
The input-output characteristics of the two devices at RT are given in Fig. 3 (a). As the current density is continuously increased from $1 \times 10^{-4}$ A/cm$^2$ to around 10 A/cm$^2$ in Fig. 3 (a), the integrated intensity over all modes increases linearly. The further increase in current density results in a super-linear increase in integrated intensity whose position we identify as the threshold current density $J_{th}$ of our laser. Finally, even higher current densities result in saturation of output power. The error bars for the integrated intensity do not appear in the diagram as they are in the range of ±5%. The lower intensity of VCSEL 2 can be explained due to the fact that the number of QDs which match optically and spatially to the mode is reduced and underlies the probability to be under the electrically pumped area. For the smallest aperture, $J_{th}$ increases to around 200 A/cm$^2$ and the obtained optical output power is obviously much smaller. This is due to the smaller active volume.

Figure 3. Integrated intensities over all modes for VCSEL 1 and 2 under dc electrical excitation at RT. The super-linear regime around and above $J_{th}$ of 10 A/cm$^2$ is a strong hint on lasing. (b) The linewidth of the fundamental mode with increasing current density is shown here for VCSEL 2. The narrowing of linewidth of the fundamental mode with increasing pump power is attributed to lasing.
Another strong indication of lasing is the linewidth sharpening by increasing current injection [17]. For this purpose, we investigated the linewidth of VCSEL 2 as shown in Fig. 3 (b). As the mode spacing is very small for VCSEL 1, we could not extract the linewidth behaviour as a function of current density in this case. By increasing the current density to 200 A/cm², the linewidth stays nearly constant within the error bars for VCSEL 2. A further increase in pump power results in a linear decrease of the spectral linewidth. This linewidth narrowing agrees well with the non-linear intensity increase of VCSEL 2 given in Fig. 3 (a). The further spectral linewidth narrowing can be understood as a consequence of a rising coherence inside the laser cavity. An increase of the current density above 310 A/cm² results in spectral linewidth narrowing down to 0.34 meV. If the injection current is further increased, the linewidth starts to broaden again due to current induced thermal effects.

5. Temperature dependent threshold current density
Finally, the threshold current density was evaluated out of the input-output curves for temperatures in a range from 100 K to 290 K. It appears that $J_{th}$ is nearly temperature independent which might originate from a broad gain contribution of the QD ensemble in general and besides from three-dimensional carrier confinement as predicted [7]. Also, lowest $J_{th}$ values of around 10-30 A/cm² were observed. The increasing $J_{th}$ for reduced aperture diameters might be correlated to non-radiative losses and scattering losses [15].

6. Conclusion
The number of QDs that match spatially and spectrally to the cavity resonance is between around 7 and 160. Such a small number of QDs can surprisingly exhibit enough gain for lasing which might be explained by nonresonant dot-cavity coupling mechanisms. It was shown that 2-4 QDs in a photonic-crystal cavity being optically pumped provide sufficient gain for lasing and they reason that with cooperation from the surrounding nonresonant QDs emission into the lasing mode becomes feasible.

We demonstrated RT lasing of red InP/(Al$_{0.20}$Ga$_{0.80}$)$_{0.51}$In$_{0.49}$P QD VCSELs. Lowest $J_{th}$ value of 9.2 A/cm² was reached and a temperature stable operation was demonstrated.

Acknowledgments
The authors gratefully thank E. Kohler, M. Ubl, J. Elling and T. Schwarzbäck for overall technical assistance and digital media support. This work was financially supported by the "BMBF EPHQUAM".

References
[1] Michler P, Kiraz A, Zhang L, Becher C, Hu E and Imamoglu A 2000 Appl. Phys. Lett. 77 184
[2] Iga K 2000 IEEE Journ. Sel. Top. Quant. Electr. 6 1201
[3] Reitzenstein S, Heindel T, Kistner C, Rahimi-Iman A, Schneider C, Höfling S and Forchel A 2008 Appl. Phys. Lett. 93 061104
[4] Hopfer F et al 2007 IEEE Journ. Sel. Top. Quant. Electr. 13 1302
[5] Iga K 2008 Japan. J. Appl. Phys. 47 1
[6] Asada M, Miyamoto Y and Suematsu Y 1986 IEEE Journ. Quant. Electr. 22 1915
[7] Arakawa Y and Sakaki H 1982 Appl. Phys. Lett. 40 939
[8] Grundmann M et al 1995 Phys. Rev. Lett. 74 4043
[9] Sellin R L, Ribbat Ch, Grundmann M, Ledentsov N N and Bimberg D 2001 Appl. Phys. Lett. 78 1207
[10] Stranski I N and Krstananow L 1938 Akad. Wiss. Wien Kl.Ib 146 797
[11] Schulz W.-M., Roßbach R, Reischle M, Beirne G J, Bommer M, Jetter M and Michler P 2009 Phys. Rev. B 79 035329
[12] Benyoucef M, Ulrich S M, Michler P, Wiersig J, Jahnke F and Forchel A 2004 New J. Phys. 6 91
[13] Bayer M, Forchel A, Réinecke Th L, Knipp P A and Rudin S 2002 phys. stat. sol. (a) 191 3
[14] Gayral B, Gérard J M, Legrand B, Costard E and Thierry-Mieg V 1998 Appl. Phys. Lett. 72 1421
[15] Hegblom E R, Babic D I, Thibeault B J and Coldren L A 1997 IEEE Journ. Sel. Top. Quant. Electr. 3 379
[16] Chung J E, Chen J, Ko P.-K., Hu C and Levi M 1991 IEEE Transactions on Electr. Devices 3 627
[17] Henry C H 1982 IEEE Journ. Quant. Electr. 18 259