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InP quantum dots for applications in laser devices
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Abstract. Single and stacked layers of InP quantum dots in (Al$_x$Ga$_{1-x}$)$_{0.51}$In$_{0.49}$P barriers were grown by metal-organic vapor-phase epitaxy for applications in semiconductor laser devices and optical gate structures. An in-plane laser structure with a single layer of InP QDs is presented, emitting at 1.942 eV and exhibiting low threshold current densities of 780 A/cm$^2$ in electrically pulsed laser operation at 288 K for a 2000 µm long device with uncoated facets. In order to realize an externally driven optical gate structure the stacking behavior of InP in (Al$_x$Ga$_{1-x}$)$_{0.51}$In$_{0.49}$P barriers was investigated. To ensure the optical addressability of each quantum dot layer, a special double dot structure where the high energetic smaller sized quantum dot is situated above the low energetic larger sized dot, was produced. The coupling between these quantum dots can be adjusted by the thickness of the spacer layer. The structures are embedded in a ni-Schottky structure and the influence of an external electric field on the emission of the quantum dot ensemble is investigated.

Due to their discrete density of states, systems of single and coupled quantum dots (QDs) are of high interest for applications in quantum information processing. Also the implementation of QDs as active medium in semiconductor lasers is a promising concept [1]. For applications in the visible spectral range the material system of InP QDs embedded in (Al$_x$Ga$_{1-x}$)$_{0.51}$In$_{0.49}$P barriers is an interesting candidate. The authors showed that in this case the emission wavelength can be tuned over a wide spectral range from red to green by changing the charge carrier confinement via the aluminum content in the barrier material and also the QD bandgap energy itself by aluminum interdiffusion into the QD for elevated growth temperatures [2]. Due to the improved charge carrier confinement for aluminum containing barriers the QDs show enhanced temperature stability and single-photon emission could be proved up to 80 K [2, 3], which makes them interesting candidates for applications in quantum information processing. The main task for future device application is to develop an externally driven optical gate. This can be realized for example by a controllable interaction (e.g. charge carrier tunneling) between vertical aligned QDs. An external electric field can influence this tunnel coupling via the Quantum Confined Stark Effekt (QCSE) [4, 5]. As our InP/AlGaInP QDs, grown by metal-organic vapor-phase epitaxy (MOVPE), exhibit high QD densities with values between 1.3·10$^{10}$/cm$^2$ and 8·10$^{10}$/cm$^2$ [2] additional structuring of the sample surface is necessary for measurements on single QDs and vertically coupled quantum dot molecules (QDMs). In contrast, for applications of InP QDs as active medium in laser structures, a high QD density is preferable. All sample structures were fabricated by MOVPE with standard precursors at low pressure.
(100 mbar) on (100) GaAs:Si substrates oriented 6° toward the [111]_A direction. For elementary studies on single and stacked layers of InP QDs, a 100 nm thick GaAs buffer layer followed by a 100 nm thick (Al_{x}Ga_{1-x})_{0.51}In_{0.49}P layer is deposited on which the first layer of self-assembled QDs is grown in Stranski-Krastanow growth mode at 650 °C or 710 °C by depositing 2.1 monolayers (ML) of InP with a growth rate of 1.05 ML/s. A growth interruption of 20 s is included to ripen the QDs. For photoluminescence (PL) measurements the samples were capped by a 30 nm thick layer of the corresponding barrier material. Fig. 1(a) and (b) show temperature dependent PL spectra for QDs grown on Al_{0.20}Ga_{0.80}InP at 650 °C and 710 °C, respectively. To perform PL measurements the samples were placed in a He-flow coldfinger cryostat and excited optically with a pulsed frequency doubled Ti:Al_{2}O_{3} laser with excitation energies of 3.10 eV and 3.14 eV respectively. The PL was dispersed by a 0.32 nm Jobin Yvon monochromator and detected using a multichannel plate photomultiplier tube. For low temperatures in both cases the emission of the barrier at 2.083 eV is clearly visible. The QD ensemble of the sample with 650 °C QD growth temperature shows emission at around 1.85 eV at 5 K. Additionally, a second emission peak at around 2.01 eV is visible. As these QDs usually show a bimodal height distribution, this shoulder can be attributed to the emission of smaller sized QDs in the ensemble. By increasing the temperature, the emission shifts to lower energies, due to bandgap shrinkage. Previous studies show, that these QDs show a high luminescence efficiency per QD with single photon emission up to 80 K [2]. In the case of higher growth temperatures (710 °C) the ensemble PL of the QDs is centered at around 2.02 eV at 4.2 K with a FWHM of 46 meV. At elevated temperatures the spectra are dominated by the emission of the barrier. The additional shoulder at around 2.04 eV can be attributed to the emission of the wetting layer (WL). By fitting gaussian distributions on the data in Fig. 1(b) the transition energy of the barrier (triangles) and the QD ensemble (boxes) can be evaluated and are displayed in Fig. 1(d). The QD emission exhibits a kink at around 100 K due to thermal excitation of charge carriers to higher energy states in the QD. The data are modelled using simplified Bose functions [8] (solid curves) with two branches for the QD emission, one for the ground state (GS) and for the excited state (ES), respectively. With values of the energetical distance between the excited states and the barrier layer of only 66 meV, the carrier confinement in the QDs is quite weak in
this case.

The presented laser structure consists of a silicon doped superlattice as buffer, followed by a separate confinement heterostructure as reported in reference [6]. The single layer of self-assembled InP QDs grown at 710 °C was placed in the center of a 20 nm thick undoped (Al_{0.20}Ga_{0.80})_{0.51}In_{0.49}P barrier surrounded by 2×150 nm thick undoped (Al_{0.55}Ga_{0.45})_{0.51}In_{0.49}P waveguide layers. The resonator structure was made by cleaving and the facets were left uncoated. The device was mounted junction-side up on a brass heatsink and contacted with a Au coated tungsten needle. Self-heating of the devices was reduced by testing them in pulsed mode with a pulsewidth of 300 ns and a repetition frequency of 10 kHz. Fig. 1(c) shows spectra of the QD laser at different drive current densities as reported in reference [6], measured with a fibre coupled spectrometer at room temperature. The current densities are calculated using the broad area stripe geometry of the top contact with a length of 2000 µm and a width of 64 µm. Current spreading is neglected, therefore the effective current density is expected to be smaller. At low current densities electroluminescence of the QD ensemble can be observed. The QD emission shift from 1.895 eV at 0.08 kA/cm² to 1.943 eV at 0.70 kA/cm², which indicates additional recombination of excitons from higher energetic states as well as the occupation of higher energetic smaller sized QDs in the ensemble. Lasing was observed at 1.942 eV for values above the threshold current density of J_{th}=0.78 kA/cm². The shift of the lasing wavelength to higher energies (ΔE=48 meV) indicates lasing from excited states, which can be confirmed due to the good agreement of the spectral position of the lasing wavelength and the emission from excited states of the QD ensemble for elevated temperatures (shown in Fig. 1(b)).

For samples with stacked layers of QDs, a (Al)GaInP spacer layer with variable thickness ranging from 2.5 nm to 20 nm is deposited after the growth of the first QD layer and the second layer of InP QDs was grown at the same temperature as the bottom layer (650 °C). It could be demonstrated in several studies, that due to the additional strain field the QDs in the second layer tend to be larger if the same amount of QD material is deposited [5, 7]. In this case the amount of deposited InP is reduced for the growth of the upper QDs to realize low energetic larger sized QDs in the bottom layer and high energetic smaller sized QDs in the upper layer. This structure was used to achieve high spectral separation of the luminescence of both QD layers in order to be able to distinguish between both QD layers even in ensemble PL measurements. To study the influence of an electric field, the QDs were embedded in the intrinsic region of a n-Schottky structure with an ohmic back contact. The additional 30 nm GaAs cap layer on top of this sample structure is removed in the region where photoluminescence measurements are performed. The top contact is processed with apertures with diameters of several µm to provide both, electric field and optical access. To achieve a homogeneous electric field the whole sample was covered with a 5 nm thick semitransparent Au layer. Previously we have proven the vertical ordering of InP QDs in GaInP barriers, due to a strain driven self-alignment, as well as the formation of quantum dot molecules (QDMs) with decreasing spacer layer thickness with an electronic coupling by a charge carrier tunneling process [9, 10]. In order to achieve enhanced temperature stability the growth of stacked layers of InP QDs in Al_{x}Ga_{1−x}InP barriers with 20 % aluminum content was investigated. The influence of the barrier thickness on the tunneling probability can already be seen in ensemble PL spectra. For ensemble PL measurements the samples were mounted in a He-flow cold finger cryostat and excited with a cw HeCd-Laser at 325 nm from the top. Therefore, electron hole pairs are mainly created in the Al_{0.20}Ga_{0.80}InP cap layer and relax first into the high energetic QDs of the upper layer. If the tunnel barrier thickness is small enough, the charge carriers are able to tunnel phonon assisted into the QDs of the bottom layer, where they recombine. Fig. 2(a) shows the ensemble PL spectra of the QD stacks with different spacer thicknesses (d_{sp}). For small d_{sp}, the luminescence spectra are dominated by the emission of the bottom layer. By increasing the spacer thickness from 2.5 nm to 20 nm the coupling strength gets weaker. The luminescence intensity of the top layer is
increasing as the probability of carriers tunnelling from the top to the bottom QD layer is reduced. By incorporating the coupled QDs with 10 nm spacing in an electrical contactable structure as described above, the changes of the PL under applied electric field can be observed (Fig. 2(b)). For 0 V bias the PL spectra shows a maximum at 1.83 eV. This emission can be attributed to the larger QDs of the bottom layer. The emission of the smaller QDs of the bottom and top layer is totally suppressed. Due to the sample structure, the band edge is tilted and the luminescence intensity is quenched. For the smaller QDs the charge carriers are able to escape into the barrier. For the larger QDs of the bottom layer the electron and hole wavefunction are strongly delocalized and the recombination rate is therefore reduced. With increasing bias voltage the PL intensity increases as the built in electric field is reduced and an additional shoulder appears on the high energetic side. This shoulder first shows an increasing intensity relative to the low energetic peak. For a bias voltages higher than 2.5 V the intensity decreases again and an increasing current can be measured. Fig. 2(c) displays the ratio $I_B/I_T$ of the integrated luminescence intensity of the bottom and the top layer. For 2.5 eV flat band condition is assumed.

We have shown, that the InP/AlGaInP QDs have the potential for either laser devices or quantum optics applications. The single layer QD broad area laser shows emission at 1.942 eV with a threshold density of 780 A/cm². Furthermore we have shown the influence of an electric field on the PL of asymmetrically QD layers. By precisely adjusting the QD growth, the spacer layer thickness, the doping and the processing of the structures, future quantum gates should be realisable in this material system.

References