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DOI:
10.1063/1.3156029

Document status and date:
Published: 01/01/2009

Document Version:
Publisher’s PDF, also known as Version of Record (includes final page, issue and volume numbers)

Orientation dependent emission properties of columnar quantum dash laser structures

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(Received 8 April 2009; accepted 28 May 2009; published online 18 June 2009)

InAs columnar quantum dash (CQDash) structures on (100) InP have been realized by gas source molecular beam epitaxy for stacking numbers of up to 24. Laser devices show low threshold current densities between 0.73 and 3.5 kA/cm^2, dependent on the CQDash orientation within the cavity. Photoluminescence and electroluminescence measurements confirm a strong relationship between the polarization degree of the emission and the orientation of the CQDashes. Eventually, the polarization of the CQDash emission could be changed from predominantly transverse electric to transverse magnetic by simply altering the dash alignment relative to the light propagation axis. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3156029]

InAs quantum dashes (QDashes) on InP have been demonstrated to show distinguished properties for 1.55 μm telecommunication applications[1–3] and particularly quantum dot (QD) and QDash based semiconductor optical amplifiers (SOAs) exhibit excellent attributes such as broadband amplification, high saturation power and fast response.[4–6] However, due to their flat shape and biaxial compressive strain, self-assembled QDs/QDashes provide dominantly transverse-electric (TE) gain[7] in guided-wave configuration, whereas polarization insensitivity is needed for SOAs in fiber communication applications.

By engineering both, shape and strain in QDs by growing either closely stacked QD layers or so-called columnar QDs (CQDs) it has been shown that polarization properties can be controlled.[8–10] With an accurate adjustment of stacking number and/or thickness and strain of the spacer layers it was demonstrated that the polarization of photoluminescence (PL) from the cleaved edge can be changed from TE to TM and even TM dominant gain has been demonstrated for InAs/InP QDs in the 1.55 μm region.[11]

In this work we report on the fabrication and characterization of columnar QDash (CQDash) based laser devices. The polarization degree of PL and electroluminescence (EL) is shown to be dependent on the orientation of the CQDashes relative to the light propagation axis. The polarization of the CQDash emission could thus be changed from TE to TM dominated by simply altering the geometrical configuration.

Samples were grown by gas source molecular beam epitaxy on (100) InP wafers. The CQDash layers were realized by alternately growing InAs QDash layers and very thin GaAs spacer layers. The nominal thickness of a single QDash layer is 0.70 nm which is slightly above the critical layer thickness so that the QDashes are fairly thin. GaAs spacer layers with a tensile strain of 3.7% where used to compensate the compressive strain of the InAs layers (3.2%) and thus to allow for closely stacking multiple QDash layers without formation of dislocations. The GaAs thickness has been varied between 0.44 and 0.78 nm for tenfold stacked CQDash structures and the optimum value was found from transmission electron microscope (TEM) and PL investigations to be 0.61 nm. For this amount the PL intensity is maximal and the InAs/GaAs superlattice between the CQDashes (i.e., the immersion layer) exhibits clearly separated layers. It is noted, that the total averaged strain of the overall InAs/GaAs superlattice is nominally zero in this case.

With these parameters stacking was performed up to 24 QDash layers as can be seen in Fig. 1 showing a cross section of the CQDash layer perpendicular to the elongated direction of the dashes. TEM investigations were made in dark field condition in which the image contrast depends on the

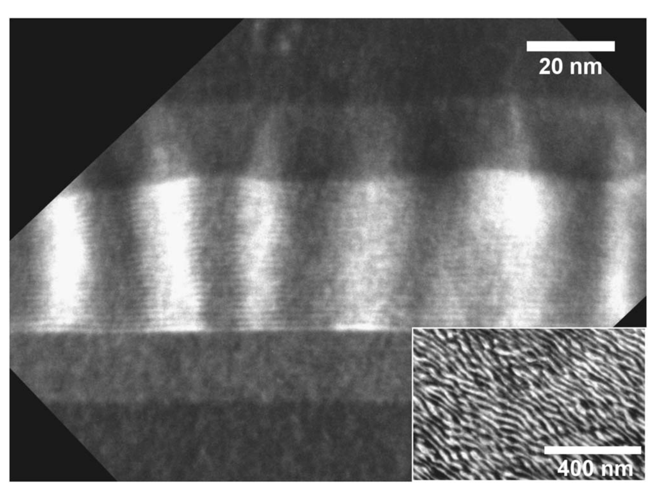

FIG. 1. TEM cross section of a 24-fold stack of CQDashes perpendicular to their elongated direction. Inset: plan view image of CQDashes.

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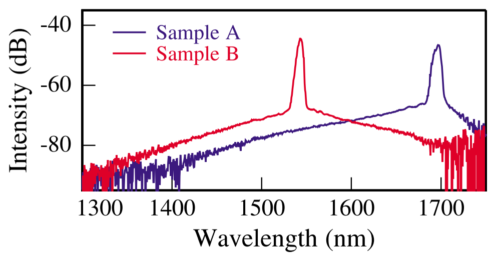

FIG. 2. (Color online) Lasing spectra of sample A (CQDashes perpendicular to laser cavity) and B (CQDashes parallel to laser cavity).

composition of the alloy and In-rich alloys appear bright. One can see fluctuations of thickness of the InAs/GaAs superlattice layer which is associated to an important lateral modulation of the In/Ga composition. The period of this modulation is about 23 nm. In fact, vertical stacking of the single QDashes within the various layers is observed which is induced by the strain fields of the QDashes of the preceding layers. The QDashes are elongated along the $[0\bar{1}1]$ direction and their length can reach several hundred nanometers (see plan-view TEM image in the inset of Fig. 1). Note the presence of a lateral modulation of composition in the upper adjacent $In_{0.53}Al_{0.24}Ga_{0.23}As$ layer induced by the stress of the stacked CQDashes and thus leading to this segregation effect. Yet, no dislocations could be observed even for stacking numbers of 24 QDash layers which confirms the high quality of the grown CQDash material.

For the realization of a laser device, two eightfold CQDash layers separated by 50 nm $In_{0.53}Al_{0.24}Ga_{0.23}As$ barriers were embedded into a 250 nm $In_{0.53}Al_{0.24}Ga_{0.23}As$ separate confinement heterostructure. This waveguide is surrounded by 200 nm InAlAs cladding layers on both sides. The top cladding is followed by 1.8 μm InP and capped with a 150 nm InGaAs contact layer. All layers, except the CQDash layer, are nominally lattice matched to InP.

Broad area lasers with 50 and 100 μm width were fabricated with either the cavity being perpendicular (sample A) or parallel (sample B) to the CQDash orientation and characterized in pulsed operation at 20 °C (0.03% duty cycle). A 1.3 mm long laser of sample A shows a low threshold current density of 0.73 kA/cm^2 and lases in TE polarization at a wavelength of 1705 nm. As one expects for QDash based lasers, the threshold current density should be higher for the dashes being oriented parallel to the cavity because the optical matrix element (and hence the gain) is smaller in this configuration.[12] In our case, because of the drive-current limitation of our measurement setup, we used a 0.6 mm long device of sample B with the back facets having a high-reflection coating that covers the whole wavelength range between 1.4 and 1.9 μm. Thus, the device has almost the same mirror losses as the laser of sample A and allows for comparability. The threshold current density of this laser amounts to 3.5 kA/cm^2. Due to the reduced CQDash gain in this geometry the lasing wavelength is significantly blueshifted to 1550 nm (see Fig. 2), which thus constitutes lasing of the quantum well such as immersion layer[13] with the polarization of the laser emission being also TE in this case.

To verify the origin of this behavior, polarization resolved PL measurements at room temperature have been performed from both, the cleaved edge perpendicular and parallel to the dash orientation. Figure 3 shows the corresponding

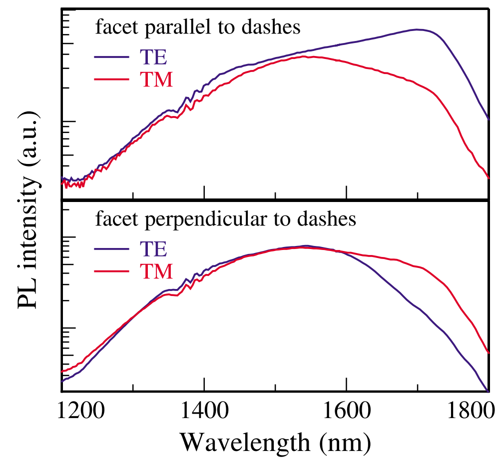

FIG. 3. (Color online) Polarization resolved room temperature PL spectra from the edge parallel (upper graph) and perpendicular (lower graph) to the CQDashes.

PL spectra at high excitation powers. The upper spectra are taken from the facet parallel to the dashes and thus correspond to laser A. One can see that the PL peak is at 1.7 μm which is also the wavelength at which laser operation starts for this CQDash orientation. The PL emission is TE dominated in this low energy part of the spectrum that originates from the "true" (i.e., three dimensionally confined) CQDash states.[13] This is due to the fact, that for this orientation the polarization is determined by the elongated extension of the CQDashes,[13] which is much larger than the vertical dimensions (about 300 nm length compared to $\sim$10 nm height).

The lower spectra are taken from the facet perpendicular to the dashes and hence correspond to laser device B. Here, the low energy part of the spectrum is highly TM polarized because now the polarization degree is changed by the significantly increased aspect ratio of the multiply stacked QDash layers. The PL total maximum, however, can be found at higher energies of the spectrum, i.e., at 1.55 μm, where lasing occurs in laser B. This spectral part is almost unpolarized as it is dominated by transitions of the more quantum well-like states of the slightly tensile strained immersion layer.[13] So the reason why lasing does not start in TM polarization on the CQDash states is because the gain of the immersion layer is slightly higher than the gain of the CQDashes for this orientation. Nevertheless, the polarization of the CQDash emission itself was changed from TE to TM dominated by changing the geometrical orientation of the dashes.

In addition to the PL investigations, polarization resolved EL measurements have been performed. Figure 4 shows the EL spectra again for both, parallel and perpendicular dash orientation, measured at a current density of 0.42 kA/cm^2. Though the optical spectrum analyzer used was limited to wavelengths below 1.75 μm, the EL spectra confirm the results from the PL. For the dashes being oriented parallel to the facet, the TE contribution is much stronger at the low energy part of the spectra than for the perpendicular alignment, thus changing the polarization degree from TE to TM dominated. The slight redshift of the emission peaks in these spectra compared to Figs. 2 and 3 is attributed to thermal heating, because of the high duty-cycle of 50% in this case, and to the different excitation level.

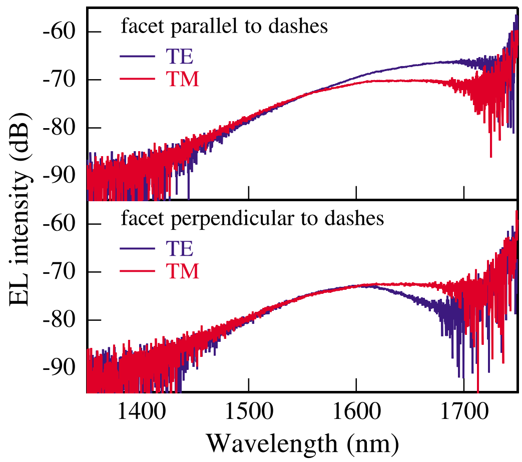

FIG. 4. (Color online) Polarization resolved room temperature EL spectra from the facet parallel (upper graph) and perpendicular (lower graph) to the CQDashes.

In summary, we have reported on the realization of CQDash based laser devices and the investigation of their PL and EL emission properties. The structures show high material quality and good lasing characteristics with low threshold currents. The TE/TM polarization degree is seen to be strongly dependent on the orientation of the CQDashes relative to the light propagation axis because of the optical matrix elements being different for the two in-plane dash dimensions. Eventually, the CQDash emission could thus be changed from TE to TM dominated by only changing the geometrical configuration. From these findings we conclude, that employing the proper stacking number of QDash layers and adjusting the angle of the CQDash alignment should allow for achieving polarization insensitive gain in the 1.55 μm range.

The authors would like to thank M. Wagenbrenner and A. Wolf for technical assistance during epitaxy and device processing. The financial support by the European Union (project "ZODIAC") and the German Federal Ministry of Education and Research (BMBF project "PKLaser") is gratefully acknowledged. Besides, P.P. acknowledges the financial support from the Foundation for Polish Science.

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