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Effect of stack number on the threshold current density and emission wavelength in quantum dash/dot lasers

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InAs quantum dash and dot (QDH and QD) lasers grown by molecular beam epitaxy on InP substrate are studied. The grown lasers with active zone containing multiple stacked layers exhibit lasing wavelength at 1.55 µm. On these devices, the experimental threshold current density reaches its minimum value for a double stacked QDH/QD structure. Other basic laser properties like gain and quantum efficiency are compared. QD lasers exhibit better threshold current densities but equivalent modal gain per layer than QDH. Finally, the analysis of the modal gain on QD laser structures shows a promising potential for improvement of the laser properties.

1 Introduction Quantum dash (QDH) and dot (QD) lasers have attracted strong attention in recent years as they are predicted to have enhanced non-linear properties compared to conventional quantum well structures [1-3]. QDH structure exhibits clearly linear polarization, while closely-stacked QDs are a potential candidate for polarization insensitive device [4]. In the last ten years, QD laser achieved great success toward 1.55 µm range for fiber-based telecommunication applications [5, 6], while QDH is also widely studied [8–10]. Tuning the emission wavelength relies on height and size control of the nanostructures. Through the double-cap technique [6] or the insertion of an ultra-thin interlayer [7], the QDH (QD) height is reduced and the homogeneity is improved. Thus, the emission wavelength can be successfully tuned from beyond 1.6 µm into the 1.55 µm range. Important issues that are crucial for telecom applications, such as low threshold current density or temperature insensitivity, have already been demonstrated for QDH based devices as for QD structures [1, 2]. Low density and inhomogeneity of QDH or QD, together with the carrier saturation in the nanostructures lead to low gain in them and thus high threshold current density (J_{th}). Therefore, stacking of layers is generally used to improve the active region volume. In addition, using InAlGaAs as waveguide enhances the energy confinement, while it results in aging problem, which is critical in the laser fabrication. For instance, aluminium can easily oxidize during laser processing or high power operation. Structural defects spread through the laser diode easily, forming light-absorbing clusters and resulting in laser degradation. In this letter, we present the investigation and comparison of J_{th} and wavelength control in QDH/QD by tuning stack number in lasers operating around 1.55 µm and based on structures with InGaAsP as waveguide. All the experimental results obtained on QDH laser are also compared to QD ones. On the other hand, Asryan's theory [11] taking into account the carrier distribution in the structures as well as the carrier capture and the excited escape into QDs is used to show that the dependence of J_{th} on the stack number is non monotonic.

2 Sample growth and laser structure The lasers were grown by gas source molecular beam epitaxy (GSMBE) on n-type (100) and (311)B InP wafers for QDH and QD respectively. The active region comprises one to five layer stacked nanostructures with a nominal deposition thickness of 2.1 monolayers of InAs per layer. The QDH/QD layers are separated by barriers of 30 nm lattice-matched $In_{0.8}Ga_{0.2}As_{0.43}P_{0.57}$ quaternary ($Q_{1.18}$; λ_g=1.18 µm). The active region is embedded into the centre of a 320 nm $Q_{1.18}$ waveguide, providing optical confinement in the transverse direction by the refractive index contrast to the cladding layers. The core structure is surrounded by 500 nm InP cladding layers on both sides. The top cladding is followed by 2.5 µm InP and capped with a 150 nm InGaAs contact layer. All layers, except the QDH/QD layers, are lattice matched to InP. The growth process was optimized by using the double-cap technique as well as controlling the arsenic flux [12]. The double-cap technique consists of a capping procedure in two steps. The first capping step is used to control the maximum height of the QDH/QD, thus allowing a reduction of the QDH/QD height dispersion. The QDH/QD formation is followed by a growth interruption under a mixed As_2 and P_2 flux, resulting in planarization of the surface due to effective As/P exchanges. The second capping step is then carried out to complete the spacer layer. The reduction of the arsenic flux results in a higher density of QDs on InP(311)B and in an improvement of the nanostructure morphology. By this means, the emitting wavelength of the laser can be tuned in the range of 1.55 µm telecommunication wavelength. A sharper gain curve can consequently be expected for the structure, which greatly eases the losses compensation. Figure 1 shows 1 × 1 µm^2 atomic force microscopy (AFM) images of uncapped (a) QDHs on (100) and (b) QDs on (311)B grown by three-fold stacked structure.

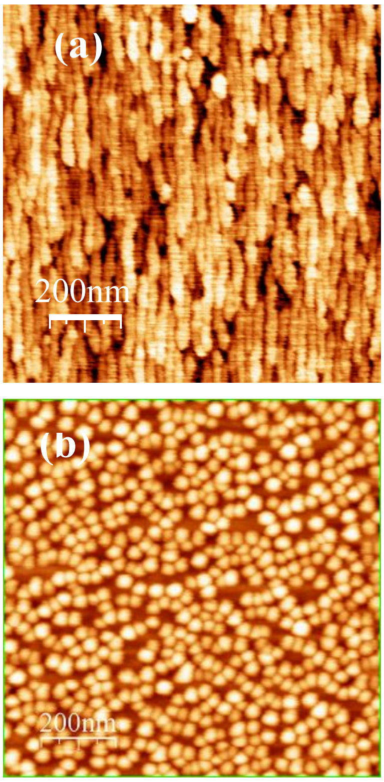

Figure 1 1×1 µm^2 AFM image of an uncapped 3 fold stacked (a) QDH and (b) QD morphology.

The morphology shows elongated QDHs with a mean height, width, and length of 2.2, 20, and 300 nm respectively. The typical area density of QDHs is 2 × 10^{10} cm^{-2}, whereas that of QDs is as high as 1 × 10^{11} cm^{-2}. In addition the size dispersion of QDs is small.

Broad area lasers were processed by a standard laser processing technique. The stripes for QDH lasers were patterned along [011] which is perpendicular to the dash elongated direction, with a width of 100 µm. This direction is chosen to obtain higher modal gain and thus lower threshold current density [13]. For QD lasers on (311)B, the stripes were along [01$\bar{1}$], as (01$\bar{1}$) planes are the only ones that could be cleaved to obtain cavity mirrors. The analysed lasers have cavity lengths between 0.8 and 3.0 mm, with both cleaved facets uncoated. The laser diodes are electrically pumped by pulsed current with 500ns pulse width and 2 kHz repetition rate.

The lasing characteristics of three layer stacked QDH/QD are first measured and compared versus cavity length and then versus number of active layer stacks.

3 Lasing characteristic versus cavity lengt

The characterization of a three-layer stacked QDH/QD lasers is systematically depicted in Fig. 2, in which the laser threshold current density at room temperature versus inversed cavity length is observed.

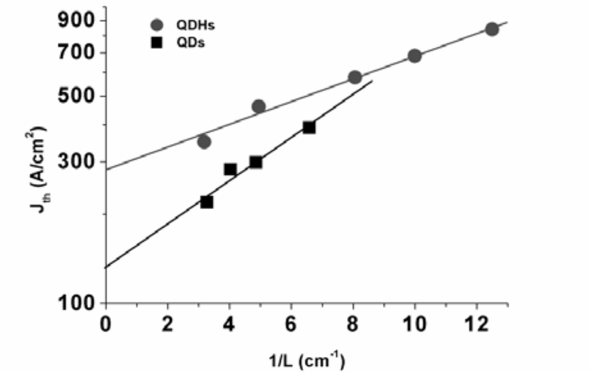

Figure 2 Threshold current density (Ln(J_{th})) versus the inversed cavity length for 3-layer stacked QDH/QD lasers (filled circles/squares). Solid lines are fits of experimental results.

Extrapolation of the dependence of J_{th} on the inverse cavity length yields the transparency current density of 280 A/cm^2 for 3-stacked QDH laser, i.e. 95 A/cm^2 per QDH layer. This value is among the best for QDH lasers operating at room temperature. The QD laser structures show a transparency current as low as 130 A.cm^{-2} for a 3 stacked layer structure (~ 45 A.cm^{-2} per stack) which is among the best results on InP substrate for QD structures.

Figure 3 shows lasing wavelength behaviour as a function of inverse cavity legth for QDH/QD lasers.The lasing wavelengths shift gradually from 1.55 to 1.52 µm when reducing the cavity length L from 0.8 mm to 2.5 mm (see Fig. 3). This situation reflects the one dimensional character of QDHs and that the carriers are more populated towards the high energy side in QDH. Comparatively, in QD active structures, only two electronic levels are found (ground state: GS and excited state: ES). The GS and ES levels overlap at room temperature due to equivalent values of inhomogeneous energy broadening and separation (25 meV). For this reason, only lasers beyond 2 mm and 1.5 mm cavity length reach GS lasing on structures containing one QD layer and three QD layers respectively. To prevent lasing on the ES during our study versus the number of stacks in the following, a margin has been taken on the mirror loss and the experimental laser length is set to 3 mm. The QD structures reach lasing even for a single stack at room temperature and the minimum threshold value occurs for a device with 2 stacked QD layers.

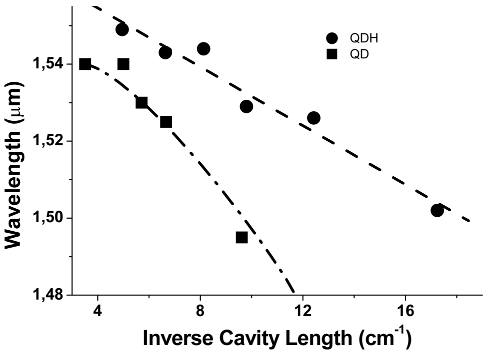

Figure 3 Laser emission wavelength versus inverse cavity length for QDH and QD.

The external differential quantum efficiency η_{ext}, is deduced from measurement of output laser light power Vs injected current curve and further the following expression:

$$\eta_{ext} = \frac{e}{h\nu}\frac{\delta P}{\delta I}$$

where e is the elementary electron charge, h is the Planck constant, ν is the light oscillation frequency and $\delta P / \delta I$ is the slope of the lasing part of the curve. The measurement was done on lasers with different cavity lengths made from a 3 QD stacks structure and a 3QDH one. In Fig. 4, is presented $1/\eta_{ext}$ as a function of the cavity length.

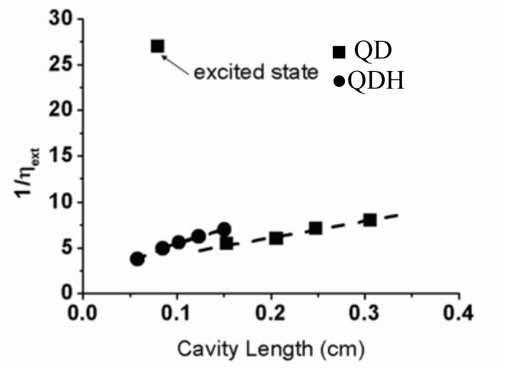

Figure 4 Inverse differential efficiency versus cavity length. The isolated point is given for a QD laser emitting on its excited state.

A linear fitting is performed according to

$$\frac{1}{\eta_{ext}} = \frac{1}{\eta_{\text{int}}}\left[1 + \frac{\alpha_{\text{int}}}{\ln\frac{1}{R}}L\right]$$

where η_{int} and α_{int} are the internal differential quantum efficiency and internal optical losses respectively and R is the mirror reflectivity. The internal loss values are evaluated to 20 cm^{-1} for QDH and 9 cm^{-1} for QD. This parameter published in the literature has a value ranging from 10 to 19 cm^{-1} [8, 10, 13]. The relatively large value of the internal losses on InP(001) substrate are similar to the values reported in the literature for equivalent QDH laser structures and can partly be attributed to residual slight misalignment of laser cavity with QDH orientation. The QDH/QD quantum efficiencies are 51 % and 40 % respectively and range from 50% to 80% in the literature [8, 10, 13].

$$J_{th} = \frac{1}{4}\frac{ezN_s}{\tau}\left(1 + \frac{N_s^{\min}}{zN_s}\right)^2 + ebBn_1 p_1 \frac{\left(1 + N_s^{\min}/zN_s\right)^2}{\left(1 - N_s^{\min}/zN_s\right)^2}$$

4 Lasing characteristic versus number of QD/QDH active layers In principle, when the QD surface density is low, it is necessary to increase the stack number to obtain enough volume of QD required to reach the laser threshold. How-ever, a gradual decrease of J_{th} with reduced stack number is experimentally observed. In the experiments for InAs QD lasers, double stacked QD laser with ultra low J_{th} of 170 A/cm^2 was demonstrated [14] while in this work a minimum J_{th} of 680 A/cm^2 for 1.2 mm long cavity is obtained and for double layers stacked QDH laser, depicted in Fig. 5. Lasing from a single QD layer as active region has already been obtained with a high QD density of more than 10^{11} cm^{-2} [15]. Similar behavior is described in quantum well lasers [16].

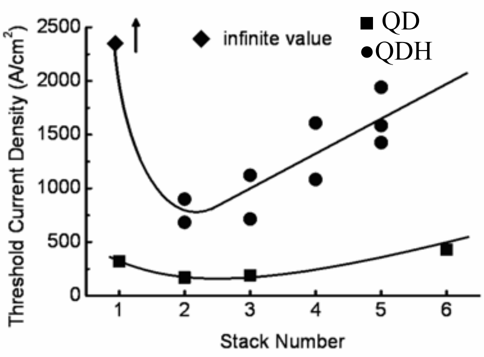

Figure 5 Threshold current density as a function of stack number for QDH, 1.2 mm cavity length and QD, 3 mm cavity length. The single stacked QDH laser shows no lasing, thus J_{th} goes to infinite value. The solid lines are guide to eyes.

As shown in Fig. 5, the results indicate a V or U-shaped dependency of J_{th} as a function of stack number. The minimum value of J_{th} exists at an intermediate stack number. Basically, the dependence of J_{th} on the stack number is non monotonic. For a very small number of stacked layers, the low value of optical confinement factor implies a strong increase of the threshold carrier density and thus with a single QD stack a higher pumping level is required to reach the laser threshold. On the other side, for larger number of stacked layers, the optical waveguide part of threshold carrier concentration decreases sharply. The injected carriers distributed effectively into the QDH/QD dominate, and J_{th} thus increases linearly with the number of stacked layers [17]. As a result, between the two extreme cases, a theoretical calculation based on Asryan's [11] model shows that the minimum J_{th} exists at intermediate number of stacks, i.e. two or three layers stacked structure will reach the lowest J_{th}, given the geometrical distribution and surface density.

To explain this, Asryan's model based on the carrier distribution in the structures and the carrier capture into QDs and excited escape from QDs is performed [11]. It should be noted that Asryan's model is developed for QD, and we applied this theory to QDH as QDH is quasi-zero-dimensional structure between QD and quantum wire. Assuming only radiative recombination under equilibrium filling at room temperature, J_{th} can be derived from the sum of current density in the QDH/QD (J_{QD}) and that in the optical confinement layer (J_{OCL}), which can be written as where B is the radiative recombination coefficient in the optical confining layer, b is the thickness of the optical waveguide, n_1 and p_1 are the electron and hole densities in the confined energy state, τ is the radiative lifetime in QDs, and z is the number of stacks. N_s and N_s^{min} represent the actuarial carrier sheet density in QDs when lasing, which corresponds to the practical parameter of surface density of QDs, and the minimum carrier sheet density required for lasing respectively. N_s^{min} is related to the size of the dot, inhomogeneous broadening, the optical confinement factor, the losses, and the stimulated emission wavelength. Due to the large inhomogeneity of QDHs, the value of N_s^{min} becomes one order of magnitude higher than that for QD lasers. The value of N_s is therefore much higher than the QDH surface density, i.e., there are a lot of carriers occupied within the same QDH when lasing.

According to the physical parameters of our samples, the value of N_s^{min} for QDH and QD lasers are estimated to be 2×10^{12} cm^{-2} and 1.5×10^{11} cm^{-2} respectively. The single layer ($z = 1$) QDH structure didn't give lasing at room temperature, probably due to the very low optical confinement factor and relatively low surface density of QDHs. Therefore, the injected carrier density into the QDHs could never succeed to be over N_s^{min} which is the condition to reach lasing. Indeed the higher value α_{int}, together with less density and less uniformity of morphology (Fig. 1) of QDH compared to QD formed on (311)B, implies that a larger N_s^{min} has to be reached for lasing, resulting in a larger value of J_{th}.

The lasing wavelengths of QDH lasers shift to longer wavelengths from 1.48 to 1.58 μm when increasing the stack number from $z = 2$ to $z = 5$, see Fig. 6.

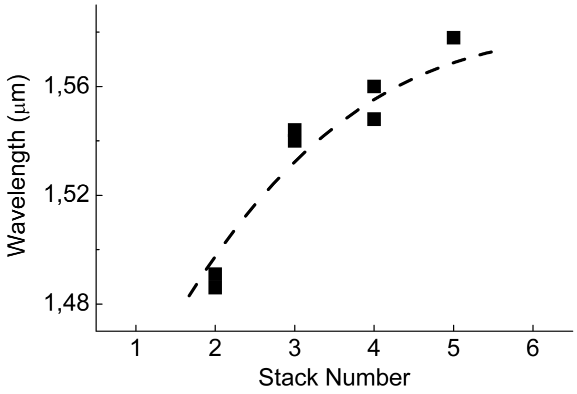

Figure 6 QDH Laser emission wavelength versus stack number.

This trend is due to the carrier redistribution between multiple layers of inhomogeneous QDHs, which is in accordance with PL measurement ones and also to the character which is not purely two dimensional in QDH structures.

The laser modal gain has been evaluated to be above 11 cm^{-1} for the structure with a single QD layer and to a maximum of 14 cm^{-1} measured on a very long single QD layer structure (4.4 mm). The typical values are above 7 cm^{-1} per layer for multi layer structures. For the QDH, the modal gain is above 8 cm^{-1} per stack for a 3 layer structure. Wang and co-workers [13] measure a value of 15 cm^{-1} for an AlInAs/InAs QD structure with one layer, this value decreases to 5.5 cm^{-1} for a structure with 5 layers, due to uneven pumping of the stacks. A value close to 7 cm^{-1} has been also measured on an InP/InAs QDH 4 layer structure [10].

Nonetheless, the results show the promising potential of QDH/QD lasers and improvement is also possible for gain values. Using the maximal modal gain obtained on our single layer QD laser structure of 14 cm^{-1} with an optical mode confinement factor of 0.43% and 80% QD carrier filling, the material gain coefficient of a single QD layer evaluates to 4000 cm^{-1}. The optical absorption coefficient value measured by a direct optical technique is 4400 cm^{-1} on a sample with a half the QD density of our structure [18]. Therefore optimized structures for better capture and injection of carriers in the quantum dot can help to improve laser properties and obtain a potential gain increase of a factor two. Then, lower thresholds and shorter cavity lengths are expected and can ease the realization of ultra fast mode-locked laser in the future.

5 Conclusion Threshold current densities of quantum dot and dash laser structures are compared. The optical gain and internal losses as well as internal quantum efficiency are measured on laser structures. Experimental results show that minimum values of threshold current densities are obtained for structures with 2 stacked layers. This is attributed to the behavior of the current density in active region which increases nearly linearly with a stack number and to the current in the waveguide region which highly increases for low gain low stack number structures. These current densities are better for QD than QDH. Analysis of experimental material gain in QD structures lead to a conclusion that a potential improvement of the laser basic properties is possible on optimized structures. This can open the way for the realization of ultra-low threshold devices in optical telecommunications.

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