Study of the characteristics of 1.55 μm quantum dash/dot semiconductor lasers on InP substrate

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InAs quantum dash (QDH) and quantum dot (QD) lasers grown by molecular beam epitaxy on InP substrate are studied. The laser active zones with 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 such as 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 lasers shows a promising potential for improvement. © *2008 American Institute of Physics*. [DOI: 10.1063/1.3005194]

Quantum dash (QDH) and dot (QD) lasers attracted strong attention in recent years as they are predicted to have enhanced nonlinear properties compared to conventional quantum well.[1–3] QDH structure exhibits clearly linear polarization, while closely stacked QDs are potential candidates for polarization insensitive devices.[4] Recently, QD (Refs. 5 and 6) as well as QDH (Refs. 7–9) lasers achieved great success toward 1.55 μm telecommunication window. The emission wavelength tuning relies on height and size control of the nanostructures. Through the double-cap technique[6] the QDH (QD) height is reduced and the homogeneity is improved. For telecom applications very low threshold current density (J_{th}) has already been demonstrated for QDH (Ref. 7) as well as for QD structures.[1,2] Low density and low size dispersion of QDH or QD, together with the carrier saturation in the nanostructures lead to low gain in them and thus high threshold current density. Therefore, stacking of layers is generally used to improve the active region volume. In this letter, we present the investigation and comparison of J_{th} control in QDH/QD by tuning stack number in lasers operating around 1.55 μm and based on structures with InGaAsP as waveguide. In addition, Asryan and Suris theory[10] is used to explain the nonmonotonic dependence of J_{th} with the stack number.

The lasers were grown on n-type InP substrate by gas source molecular beam epitaxy with (100) surface orientation for QDHs and (311)B for QDs. The active region comprises one to five stacked layers with a nominal deposition thickness of 2.1 ML (monolayer) of InAs per layer. The QDH/QD layers are separated by 30 nm barriers of lattice-matched $In_{0.8}Ga_{0.2}As_{0.43}P_{0.57}$ quaternary (Q1.18; $\lambda_g = 1.18$ μm). The active region is centered in the 0.32 μm thick Q1.18 optical waveguide. The core structure is surrounded by InP cladding and the top InP is 2.5 μm thick and is capped with a 0.15 μm InGaAs contact layer. The optimized growth process uses the double-cap technique as well as the control of the arsenic flux[11] to tune the wavelength and to optimize the density. By this means, the emitting wavelength of the laser can be tuned to the 1.55 μm spectral window. Figure 1 is 1×1 μm^2 atomic force microscopy (AFM) images of uncapped (a) QDHs on (100) and (b) QDs on (311)B grown by threefold stacked structure. The morphology shows elongated QDHs with a mean height, width, and length of 2.2, 20, and 300 nm, respectively. Typical areal densities are 2×10^{10} cm^{-2} for QDHs and are as high as 1×10^{11} cm^{-2} for QDs.

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 J_{th}.[12] For QD lasers on (311)B, the stripes were along $[01-1]$, as $(01-1)$ planes are the unique cavity mirror cleavage planes. The cavity lengths vary between 0.6 and 3.0 mm, with both cleaved facets left uncoated. The J_{th} measurements in this paper are carried out at room temperature (RT) and at the same cavity length of 1.2 mm for QDH lasers, and 3.0 mm for QD ones. The laser diodes are electrically injected by pulsed current with 0.5 μs pulse width and 2 kHz repetition rate.

Figure 2 shows a V or U shaped dependency of J_{th} as a function of stack number z and dash as well as dot structures presents similar behaviors. The QD structures reach lasing at RT even for a single stack and the minimum threshold values occur near $z=2$. Due to a higher QD density and to a different carrier energy distribution, the value of J_{th} is lower for QD than in QDH. In QD active structures, only two electronic levels are found (ground state: GS and excited state:

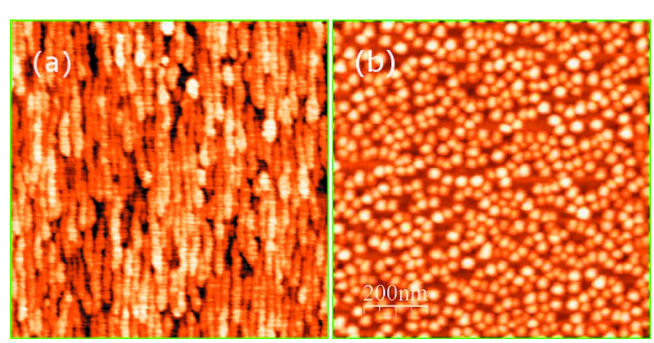

FIG. 1. (Color online) 1×1 μm^2 AFM image of an uncapped threefold stacked (a) QDH and (b) QD morphologies.

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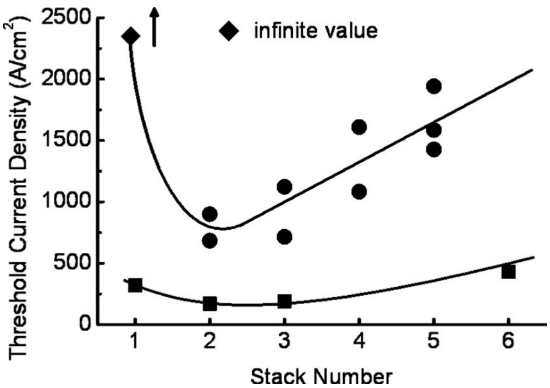

FIG. 2. RT threshold current density as a function of stack number for QDH (filled circle, 1.2 mm cavity length) and QD (filled square, 3 mm cavity length). The single stacked QDH laser shows no lasing, and thus J_{th} goes to infinite value. The solid lines are guides for the eyes.

ES). The GS and ES levels overlap at RT due to close values of energy broadening and separation ($\sim$25 meV). Thus, only lasers beyond 2 and 1.5 mm cavity lengths reach GS lasing on structures containing one QD layer, and three QD layers respectively. To prevent lasing on the ES during our study, a margin has been taken on mirror losses and laser lengths are set to 3 mm. For InAs QDs, double stacked laser with ultralow J_{th} of 170 A/cm^2 was demonstrated[13] while in this work a minimum J_{th} of 680 A/cm^2 for 1.2 mm long cavity is obtained and for double stacked QDH structure. A high QD density of more than 10^{11} cm^{-2} has previously allowed lasing of a single QD layer.[14]

Figure 3 gives experimental results on three-layer stacked QDH/QD lasers. Figure 3(a) depicted J_{th} versus $1/L$, the inverse cavity length, performed at RT. The exponential dependence of J_{th} with $1/L$, extrapolated to zero, yields the current density for infinite length of 280 A/cm^2 for three-stacked QDH laser, i.e., $\sim$95 A/cm^2 per QDH layer. The QD lasers show a current density for infinite length as low as 130 A/cm^2 for a three-stacked layer structure ($\sim$45 A/cm^2 per stack) which is among the best QD result on InP substrate. The QDH lasing wavelengths shift gradually from 1.55 to 1.52 μm when reducing the cavity length L from 2.5 to 0.8 mm. This situation reflects that the carriers are more populated toward the high energy side in QDH while the wavelength is relatively stable in QD cavities reflecting the different nature of energy states.

The external differential quantum efficiency η_{ext}, is deduced from measurements on laser with different cavity lengths for a three stack structure. In Fig. 3(b), $1/\eta_{ext}$ is presented as a function of the cavity length. A linear fitting is performed according to $1/\eta_{ext}=1/\eta_{int}[1+\alpha_{int}L/\ln(1/R)]$, 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 losses values are evaluated to 20 cm^{-1} for QDH and 9 cm^{-1} for QD. This parameter published in the literature has values ranging from 10 to 19 cm^{-1}.[7,9,11] The internal losses on InP (001) substrate are similar to the values reported in the literature for equivalent QDH laser structures, and their large value 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.[7,9,11]

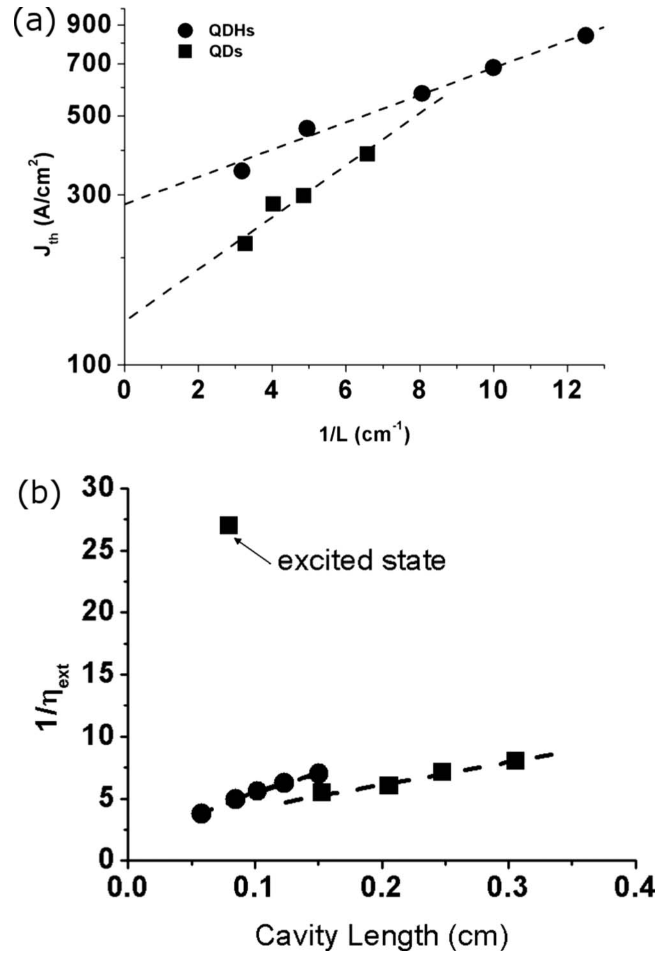

FIG. 3. (a) J_{th} at RT vs the reciprocal length for three-layer stacked QDH/QD lasers (filled circles/squares). The dashed lines are exponential fits of experimental results. (b) External quantum efficiency vs cavity length (QDH/QD: filled circles/square). The isolated point is given for a QD laser emitting on its ES.

Using QDHs, one will get higher efficiency, higher modal gain, but higher losses and higher J_{th}, which is not so obvious. According to the model of Asryan and Suris,[10] the current density writes as $J_{th}=J_{QD}+J_{OCL}$ where the first component originates from QDH/QD and the second from the optical confinement layer. In this model, the total number of carriers in QDH/QD (zN_s, N_s: carrier number in a QDH/QD layer) is the key parameter for laser basic properties. The minimum comes from the quasilinear J_{QD} increase with z for a fixed carrier density at high stack values ($z>3$) as previously observed[15] and the quadratic increase in J_{OCL} with current at high levels for low gain cavities (low z and low cavity lengths). This model shows that a minimum total number of carriers N_s^{min} is required for lasing. This minimum is related to the size of the dot, its size fluctuation, the optical confinement factor, the losses, the stimulated emission wavelength, etc. The minimum J_{th} of QDHs is one order of magnitude higher than that of QDs, which is believed to be due to the larger size dispersion of QDHs. The value of N_s is therefore much higher than the QDH surface density, i.e., there are many carriers 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} and 1.5×10^{11} cm^{-2}, respectively. The single QDH layer ($z=1$) did not give lasing at RT, probably due to its very low optical confinement factor and to its relatively low surface density. Finally, the higher α_{int} value, as mentioned above, together with less density and less uniformity of QDH morphology (Fig. 1) compared to QD formed on (311)B, implies that a larger N_s^{min} has to be reached for lasing, resulting in a larger J_{th}.

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 multilayer structures. For the QDH, the modal gain is above 8 cm^{-1} per stack for a three layer structure. Wang *et al.*[12] measured a value of 15 cm^{-1} for an InAs/AlInAs QD structure with one layer, this value decreases to 5.5 cm^{-1} for a structure with five layers, due to uneven pumping of the stacks. A value close to 7 cm^{-1} has been also measured on a four layer InAs/InP QDH structure.[9]

Nonetheless, the results show promising potential improvements on laser gain values. Using the maximal modal gain obtained on a 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 measured by a direct optical technique is 4400 cm^{-1} on a sample with a half the QD density of our structure.[16] Therefore optimized structures for better capture and injection of carriers in the QD can help to improve laser properties and obtain a potential gain increase in a factor of 2. Then, lower thresholds and shorter cavity lengths are expected and can ease the realization of ultrafast mode-locked lasers in the future.

In conclusion, threshold current densities of QDH and QD lasers are compared. The optical gain, internal quantum efficiencies, and losses are measured. Experimental results show that minimum values of threshold current densities are obtained for structures with two 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 leads 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 ultralow threshold devices for optical telecommunications.

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