Enhanced Performances of Quantum Dot Lasers Operating at 1.3 μm

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***Abstract*—Due to their δ-like density of states, quantum dots (QDs) were expected to improve laser device performances with respect to quantum wells (QWs). Nevertheless, some important drawbacks limit this technology. For instance, QD laser still suffers from a low value of the modal gain, due to the low areal density of QDs, and inhomogeneous broadening, especially when multistacked layers are used. In this paper, we demonstrate that a linear increase of the QD modal gain with the QD layers number, as typically achieved in multi-QW lasers, is possible by a careful control of the Stranski–Krastanov QDs growth and QDs stacking optimization. A low-transparency current density of 10 A/cm^2 per QD layer and a modal gain of 6 cm^{-1} per QD layer were achieved from laser structures containing up to seven QD layers. We demonstrate 10-Gb/s direct modulation (until a temperature of 50 °C) and high T_0 (110 K) from a single-mode device containing six QD layers.**

***Index Terms*—Modal gain, quantum dots (QDs), semiconductor laser, threshold current.**

I. Introduction

SEMICONDUCTOR laser is a key device in optoelectronics because of its high quantum efficiency and pure output spectrum. Since their first proposal by Arakawa *et al.* [1], quantum dots (QDs) in the active zone of semiconductor lasers are expected to show higher performances as compared to quantum wells (QWs), in terms of high gain, high efficiency, ultralow threshold current densities, narrow chirp characteristics, and temperature-insensitive operation [1], [2]. Some of these advantages have recently been demonstrated in fabricated devices [3]–[11]. However, several issues are still open and make the fabrication of such devices challenging. In order to definitely overcome QW laser performances and gain the optoelectronics market, the QD technology needs some important steps forward such as the enhancement of modal gain, high-temperature stability, and fast frequency response.

The accomplishment of such results is crucially related to the epitaxial growth of the QD-based active material. So far, Stranski–Krastanov growth mode is the established technique for the realization of QD arrays. Several parameters are involved in this kind of growth, making difficult the control of the island formation and self-organization. For this reason, it is hard to improve the areal density to more than 10^{10} cm^{-1} (typical of the InAs/GaAs case-study system), while keeping, at the same time, a narrow distribution. Therefore, in spite of the expected theoretical δ-like emission spectrum, broadened features are usually obtained by an epitaxial QD ensemble, due to the large size/composition distribution of these nanostructures (i.e., inhomogeneous broadening).

Because of this problem, QD lasers still suffer from a low value of the modal gain (typically 3 cm^{-1} per QD layer in a multi-QD laser) [12], [13], due to the low areal density of QDs and to the dispersion in their size and composition. These drawbacks result in the achievement of laser action only in low-loss cavities, requiring the use of high-reflectivity coatings to obtain short-cavity devices [14]. A low inhomogeneous broadening was demonstrated for QD single layer [15]. Therefore, to improve laser performances, the best solution is to stack many QD layers [16], [17]. In this case, a careful optimization of the growth conditions and of the active region design is necessary because QD formation is very sensitive to the strain field inside the structure. The main point is the ability to recover the same surface and strain conditions for each QD layer constituting the multistack. In fact, so far, no multi-QD lasers have been realized as an 0-D counterpart of mutiple QW (MQW) devices, where the linear dependence of maximum modal gain on the QW number is well established.

Along with the complexity related to QD growth, this material system is also a subject of intense investigation on its optical properties, which are crucial for the improvement of

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optoelectronic device performances. Carrier dynamics, such as capture time, intrinsic radiative decay time, and intraband relaxation time, determine, for instance, the maximum frequency response and the maximum achievable modal gain, and are strongly dependent on the QD growth procedure.

In this paper, some of the several issues concerning 1.3-μm QD lasers are explored. We first report on the growth process to achieve highly dense and uniform QD layers, focusing on a particular stacking procedure that is found to be very effective in improving the properties of QD-based active zones and laser devices, demonstrating the possibility to linearly increase the modal gain as a function of the QD layers. The optimization of the growth conditions allows keeping constant the inhomogeneous line broadening at a low value (<30 meV) even for a stack of seven QD layers. A transparency current density and a modal gain per QD layer of 10 A/cm^2 and 6 cm^{-1}, respectively, were achieved at room temperature and at 1.3 μm. The fabrication of a single-mode device allows the demonstration of 10-Gb/s direct modulation at 15 and 50 °C, with a T_0 of 110 K in a wide operating temperature range.

Device performances have been tentatively attributed to the QD carrier dynamics, deduced by time-resolved photoluminescence and by absorption measurements.

The paper is organized in four sections. Section II deals with growth optimization of single and multiple QD layers. Section III concerns optical investigation of carrier dynamics, while Section IV is dedicated to device performances. The results are finally summarized in Section V.

II. Growth of Single and Multiple QD Layers

The most used method to fabricate QDs is the Stranski–Krastanov (SK) growth, typical of lattice-mismatched systems [18], which has allowed the realization of defect-free QDs. The InAs/GaAs system is a perfect model for which the SK method is applied and also this system allows reaching the strategic telecommunication wavelength of 1.3 μm.

For this study, InAs QDs were grown by molecular beam epitaxy (MBE) in a Riber Compact 21T system equipped with an arsenic cracker generating As_2 as a V-element source.

The growth temperature, the growth rate and the InAs thickness were varied separately in order to obtain a uniform size distribution of the QDs. The atomic force microscopy (AFM) analysis of the grown samples shows that the best results in term of size uniformity and a high density of QDs are obtained with InAs growth rate of ~0.04 ML/s, growth temperature <500 °C, and InAs thickness of 2.8 MLs. Statistic analysis, performed by software, reveals a uniform distribution, with mean height of 5 nm, average diameter of 45 nm, and a QD density of $\sim 4 \times 10^{10}$ cm^{-2}. The inset of Fig. 1 shows the AFM image of an uncapped reference sample.

The capping procedure is crucial to obtain high photoluminescence (PL) emission. The growth rate of the GaAs and the V/III flux ratio were fixed at 0.5 μm/h and 20, respectively. Between QDs and GaAs cap layer, a growth interruption of 90 s, under the same As flux used for InAs QDs, provides the optimum result in terms of narrow line width and high efficiency. The insertion

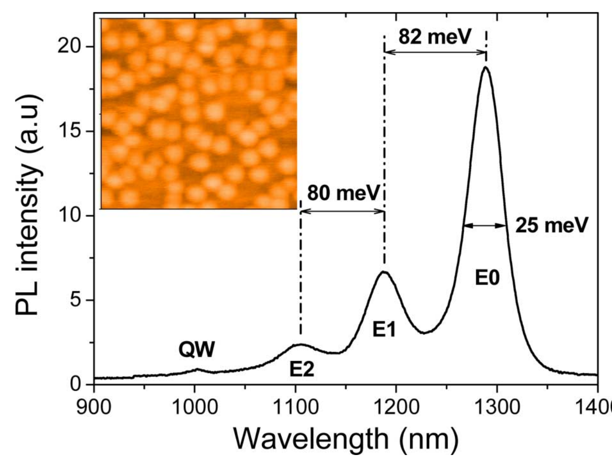

Fig. 1. Photoluminescence emission of a reference sample containing 1 QD layer at room temperature. The inset is an AFM image (0.5×0.5 μm^2) of an uncapped reference sample.

of these QDs in a GaAs barrier provides at room temperature a PL emission wavelength from the ground state not longer than 1250 nm, with a full-width at half-maximum (FWHM) of 24 meV. In order to red-shift the emission wavelength beyond 1.3 μm, the strain reducing layer technique [19] was chosen and InAs QDs have been capped with few-nanometer-thick layer of $In_xGa_{1-x}As$. An indium content of 18% was used to reach wavelength emissions at 1.3 μm. The optimum thickness of $In_xGa_{1-x}As$ layer was in the range of 4–5 nm. The pause time after the QDs was kept constant. Fig. 1 shows the room temperature PL emission of a reference sample containing 1 QD layer. The ground, first and second excited states emit at 1289 nm, 1186 nm, and 1105 nm, respectively (962 meV, 1045 meV, and 1122 meV, respectively). It is important to point out that the energy difference between the ground and the first excited state of 82 meV is quite large as compared to the values reported in the literature (less than 70 meV). The FWHM of the PL emission is as low as 25 meV, which demonstrates the good size uniformity of these QDs.

As stated earlier, one of the main problems of QD lasers is gain saturation [12], [13]. It is necessary to increase the optical gain in a QD laser structure by increasing the QD number by stacking several QD layers.

In order to ensure a very good layer-by-layer reproducibility, the spacer layer thickness and the growth temperature should be optimized. A series of samples having different spacer layer thickness (ranging from 5 to 65 nm) and containing three QD layers were grown. For all samples, the first 5 nm were grown at the same temperature of the QDs followed by a pause under As_2 flux long enough to increase the substrate temperature up to ~600 °C for the growth of the remaining GaAs barrier. The 5 nm of GaAs grown at low temperature was used to protect the InAs QDs capped with InGaAs and to avoid InAs evaporation. The normalized PL intensities to one QD layer show that all samples have a PL intensity higher than the reference single-QD-layer sample, except for the sample with 5-nm-thick GaAs barrier. In addition, the FWHM decreases with increasing the barrier thickness and it reaches a value of 26 meV for a barrier

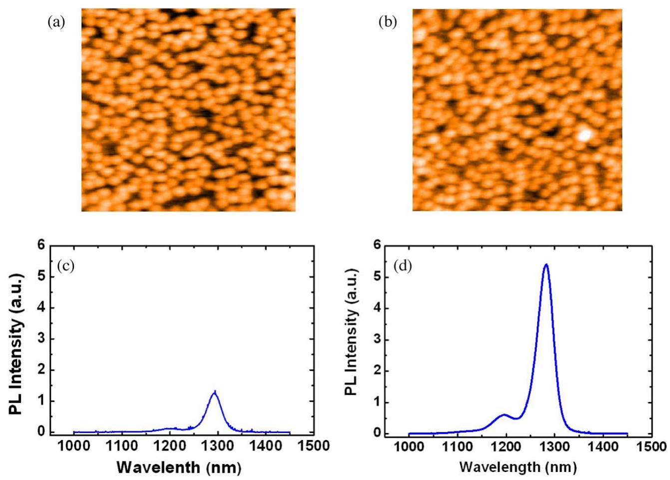

Fig. 2. (a) and (b) show AFM images ($1 \times 1\ \mu m^2$) of two samples containing two and seven QD layers, respectively (the last uncapped). (c) and (d) show the corresponding PL emissions at room temperature.

thicker than 40 nm. Based on these results, for the growth of the laser structures, we fixed the GaAs barrier thickness to the value of 40 nm, which provides the optimum value for FWHM and PL intensity.

Anyway, the use of a higher barrier thickness would limit the number of QD layers since the waveguide thickness is limited to few hundred nanometers. In addition, since the modal gain is proportional to the confinement factor of the QD layers, the use of a thick GaAs spacer layer limits the overlap of the optical field on the QD away from the center of the waveguide. Therefore, the use of higher barrier thickness imposes a limit on the number of QD layers in the same active region.

Using these conditions, we have stacked up to seven layers. From PL and AFM analysis performed on two samples containing seven QD layers (the last uncapped), we did not observe any degradation of the optical and structural properties with respect to the single-layer sample. The QD density remains constant, as indicated in Fig. 2(a) and (b). In addition, the PL intensity increased by a factor of ~6 with respect to a single-QD layer, as indicated in Fig. 2(c) and (d), with a FWHM of only 29 meV. These results prove the possibility to stack up to six QD layers without altering the single-layer morphological and optical properties.

III. Carrier Dynamics

The study of carrier relaxation in QD nanostructures is very important to improve the PL efficiency and the performances of the optoelectronic devices. For instance, the capture and relaxation of carriers from the barrier states into the discrete energy states involved in lasing, is a crucial issue affecting the maximum frequency response of the devices. A cascade process has generally been found involving carrier–carrier scattering (Auger effect) [20], [21] or multiphonon emission [21], [22]. Other studies have found a simultaneous filling of the QD levels with a long (few tens of picoseconds) capture time dominated by the diffusion time in the GaAs barrier [23] or attributed to multiphonon relaxation of the excited hole states [24]. An efficient Auger relaxation has also been invoked in order to explain the fast capture time [25].

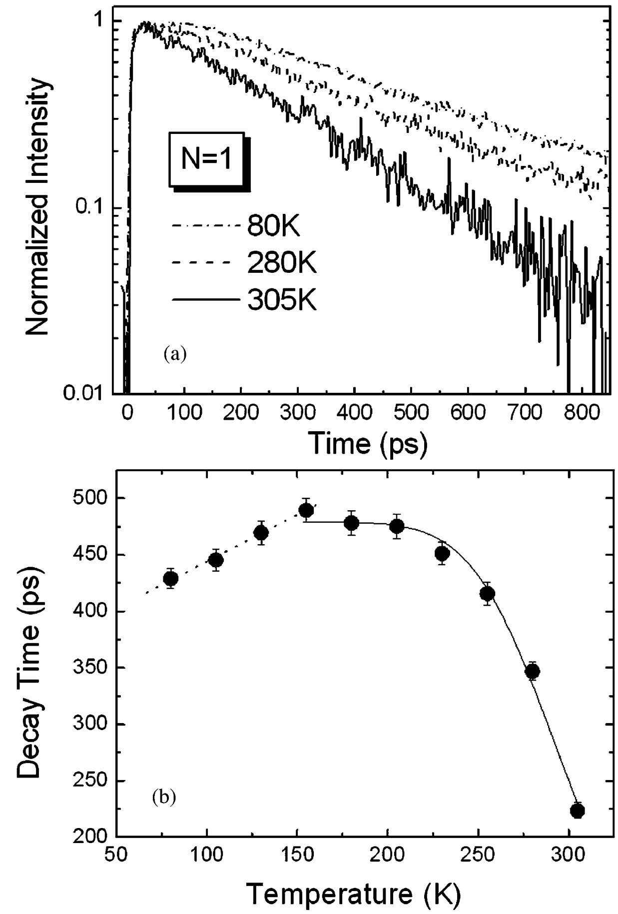

Fig. 3. (a) Normalized ground-state PL transient versus time at various temperatures. (b) Temperature dependence of the decay time. The continuous line represents the best fit obtained by the Arrhenius plot.

For carrier relaxation study on our structures, time-resolved PL upconversion measurements were performed by using a mode-locked Ti:Sapphire laser (80 fs pulses at 80-MHz repetition rate) tuned at 780 nm. The emission of the QDs was upconverted with a time-delayed portion of the excitation beam in a 2-mm-thick b–barium–borate (BBO) crystal. The upconverted PL light was detected by a monochromator and a cooled GaAs photomultiplier in a single-photon counting mode. The temporal resolution of the experimental setup was better than 200 fs. In-plane absorption measurements were also performed.

Fig. 3(a) shows the normalized time-resolved PL spectra of the ground state (N = 1) as a function of temperature for excitation power density of about 860 W/cm^2. Fig. 3(b) displays the temperature dependence of the decay time obtained by fitting the PL decay profile to a single exponential function. At 80 K, a radiative decay time of about 430 ps is observed. So, a high radiative rate is expected to positively affect the maximum achievable modal gain in QD laser devices. With increasing temperature from 80 K to 170 K, a linear increase of the radiative decay time occurs up to 500 ps. This behavior is attributed to carrier transfer among different QDs. With increasing temperature,

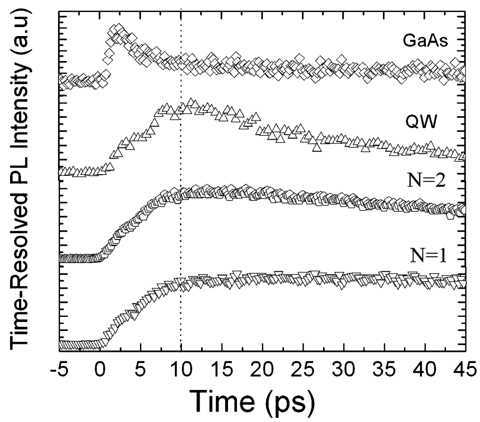

Fig. 4. Room temperature time-resolved PL measurements at different detection energies. The dotted line is a guide for eyes.

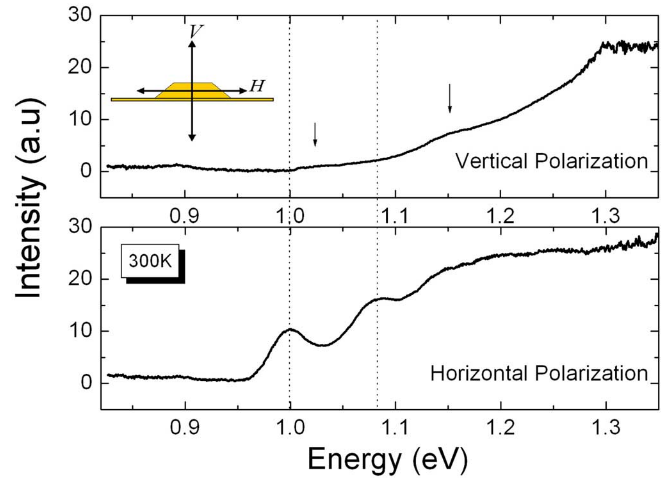

Fig. 5. Room temperature absorption measurements for both normal (V) and in plane (H) states of polarization.

the carriers can escape from the smaller (higher energy) QDs and they can be recaptured by the larger ones (lower energy). Since the larger QDs have lower transition rates (due to the lower overlap between the electron and hole wavefunction), the carrier transfer from the latter to the former causes a slight increase of the radiative decay time [26]. For $T > 200$ K, the rapid decrease of the PL decay reveals that thermal escape becomes the dominant nonradiative mechanism. By fitting the data to the Arrhenius plot, activation energy of about 290 meV has been found. This is consistent with energy splitting between the QD ground state and the InGaAs QW lowest state. In order to study the carrier relaxation pathway, time-resolved experiments are performed at different detection energies.

Fig. 4 shows four time-resolved traces on a time scale of 45 ps at the ground state, first excited state, QW, and GaAs barrier emission energy, respectively. The rise times of the QD states and of the QW band-edge are nearly identical, with typical values of: 5.94 $\pm$ 0.21 ps, 6.3 $\pm$ 0.16 ps, and 6.19 $\pm$ 0.26 ps for the ground state, first excited state and QW transition, respectively.

Therefore, no sequential PL rising time is observed at least for the relatively high power density needed to perform upconversion experiments. The results suggest that the carriers can cool down simultaneously to any lower QD energy states. The total rise time ($\sim$2 ps) and decay time ($\sim$4 ps) of the GaAs emission are indeed consistent with such a carrier dynamics. In this picture, the QD excited states do not act as an intermediate stage, while the direct carrier capture occurs through a finite continuum of density of states, as already observed by Toda *et al.* [27]. Alternatively, it could be related to the existence of intrinsic crossed transitions of hybrid dimensionality (0-D–2-D) between the bound QD states and delocalized states, as proposed by Vasanelli *et al.* [28]. The fast capture, probably mediated by a continuum of hybrid 0-D–2-D states, shows the potential for high modulation speeds in our 1.3-μm QD devices.

In order to verify the existence of a continuum of states in the spectral region of the QD transition energies, we have performed absorption measurement, which is directly connected to the density of states of the material. Due to the poor overlap of the active material with a normally transmitted probe beam, absorption measurements based on normal incidence are very noisy and even hard to perform. So, these problems were overcome by changing the experimental configuration and by adopting a waveguide structure to enhance the interaction probability. Fig. 5 shows the obtained absorption spectrum for both in plane (perpendicular to the growth direction) and normal (parallel to the growth direction) state of polarization. In-plane polarized light is evidently much more absorbed by QDs and two well-resolved peaks are observed, which are attributed to the ground and first excited state. The polarization-dependent absorption can be attributed to their flat shape and quasi-biaxial compressive strain, determining a valence-band ground state of the heavy hole, which does not couple to light polarized along the growth axis. Remarkably, in each case, a broad smooth absorption background is evident, which is explained considering crossed transitions between the bound QD states and delocalized states.

IV. QD Laser Performances

The laser structures were grown by MBE on 2-in Si-doped (1 0 0) GaAs wafers. They consist of: a 200 nm-thick n-type GaAs buffer, a 1.5-μm-thick $Al_{0.4}Ga_{0.6}As$ n-type (5×10^{17} cm^{-3}, Si) cladding layer, an undoped active zone with one, three, five, six, or seven stacked InAs/$In_{0.18}Ga_{0.82}As$ QD layers separated by 40-nm-thick GaAs electronic barriers and enclosed between GaAs spacers, a 1.5 μm-thick p-type $Al_{0.4}Ga_{0.6}As$ (2×10^{18} cm^{-3}, Be) cladding layer, and, finally, a 300 nm p$^+$-GaAs cap layer. Broad-area lasers were fabricated from the grown wafers (for the structures containing one, three, five, and seven QD layers). Single-mode devices were processed from the structure containing six layers of QDs in order to perform high-frequency modulation measurements.

From light–current characteristics measured in devices with different cavity lengths (L) at room temperature, we have estimated the external differential quantum efficiency $\eta_{\rm d}$. The internal loss $\alpha_{\rm i}$ and the internal quantum efficiency $\eta_{\rm i}$ were obtained from the 1/$\eta_{\rm d}$ (L) dependence. Fig. 6(a) shows the reciprocal

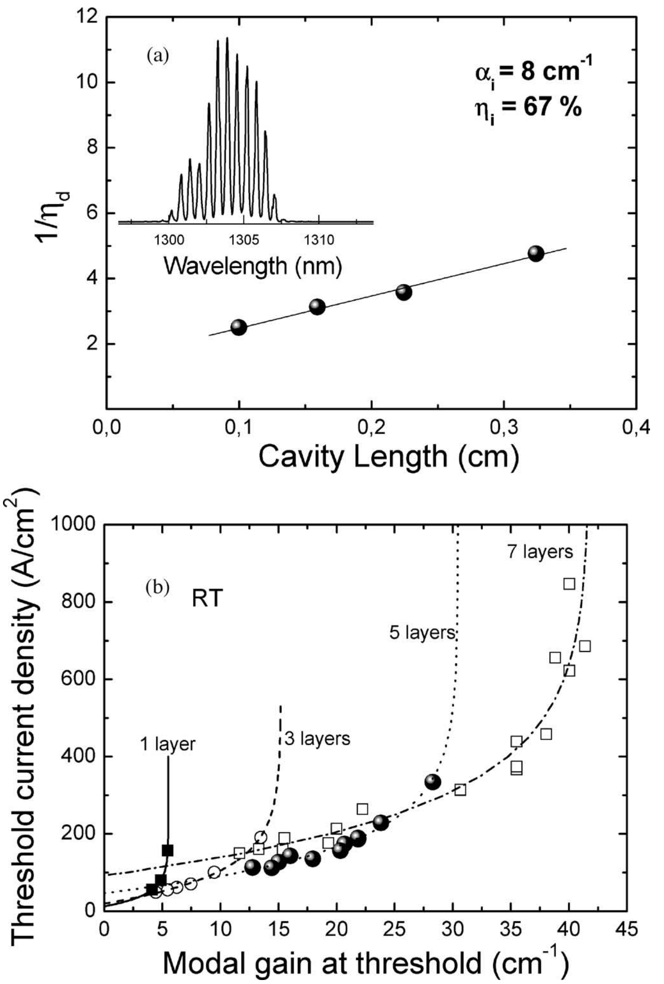

Fig. 6. (a) Reciprocal differential quantum efficiency as a function of cavity length for the laser structure containing seven stacked QD layers. The inset shows ground state laser spectrum for the shortest device (120×360 μm^2) with uncoated facets. (b) Threshold current density as a function of the modal gain at threshold for a series of lasers containing one, three, five, and seven QD layers.

differential quantum efficiency $1/\eta_\mathrm{d}$ as a function of the cavity length for laser devices containing seven stacked QD layers and the ground state laser spectrum for the shortest device (120×360 μm^2) with uncoated facets. The measurements were performed with a duty cycle of 0.2% and pulse width of 2 μs, at room temperature. From this plot, η_i and α_i were deduced using the well-known relation $\eta_\mathrm{d} = \eta_\mathrm{i}/[1 + \alpha_\mathrm{i} L/\ln(1/R)]$, where L is the cavity length and R is the power reflectivity of the as-cleaved facets ($R = 0.30$). The linear fit yields an η_i of 67% and an α_i value of $\sim$8 cm^{-1}.

The modal gain of the broad-area lasers was calculated by measuring the threshold current density for different cavity lengths and by using the internal losses estimated earlier. As at threshold the modal gain compensates the total losses, we have built the dependence of the threshold current density on the modal gain, as depicted in Fig. 6(b). The data were fitted to the empirical expression

$$J_\mathrm{th} = J_\mathrm{tr} + \frac{J_\mathrm{tr}}{\gamma} \ln\left(\frac{g_\mathrm{sat}}{g_\mathrm{sat} - g_\mathrm{mod}}\right) \quad (1)$$

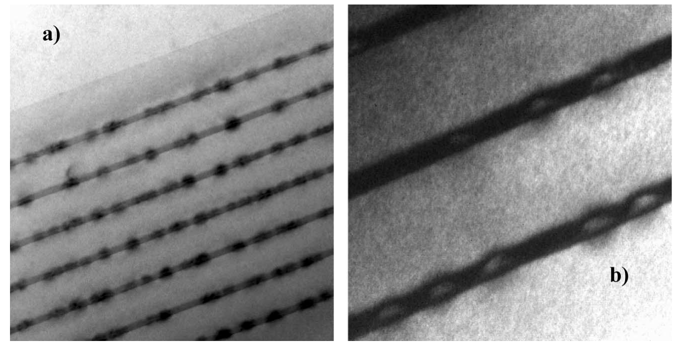

Fig. 7. (a) Bright-field and (b) dark-field cross-sectional TEM images of the laser structure containing seven QD layers.

where g_mod is the modal gain, g_sat is the saturation modal gain, γ is a nonideality factor (its value should be of the order of unity in real QD arrays), J_th is the threshold current density, and J_tr is the transparency current density [12]. We have derived a saturation modal gain of 5.5, 15, 30, and 42 cm^{-1} for the laser structures containing one, three, five, and seven QD planes, respectively, which corresponds to $\sim$6 cm^{-1} per QD layer. The minimum cavity length for which the laser action from the ground state was achieved, decreases with increasing the QD layer number. The shortest cavity was 360 μm for the laser structure containing sevem QD layers, whereas it was relatively long for the laser containing a single-QD layer (3 mm). The high modal gain was achieved with a standard QD density ($\sim 4 \times 10^{10}$ cm^{-2}). Recently a modal gain of 54 cm^{-1} was obtained with higher QD density ($\sim 8 \times 10^{10}$ cm^{-2}) and a laser device containing nine QD layers [29], [30]. In this device the shortest cavity length for which the ground state lases is 700 μm.

In addition, the QD density in the samples presently investigated keeps low the value of the transparency current densities. In fact, the transparency current density of the four laser structures increases with the number of QD layers. Their values are 12 A/cm^2, 19 A/cm^2, 45 A/cm^2, and 92 A/cm^2 for the laser structures containing one, three, five, and seven QD layers, respectively. These values are very low in comparison with the values reported in [29]. Cross-section transmission electron microscopy (TEM) was performed on the laser structures containing seven QD layers. Fig. 7(a) shows a bright-field cross-sectional TEM image. It demonstrates that the InGaAs QWs have sharp interfaces and the strain field is localized into the well width. It appears from the image that there is no correlation between the QD layers, as expected by the chosen GaAs barrier thickness of 40 nm. The QD density remains constant. Fig. 7(b) shows a dark-field image of the first and the second QD layers. The QDs are lens shaped with a flat bottom; they have a dot base length of $\sim$15 nm and a height of $\sim$8 nm.

In Fig. 8 we have plotted the modal gain normalized to one QD layer as a function of the threshold current density. The data corresponding to the four laser structures containing one, three, five, and seven stacked QD layers could be fitted by one curve from which we can deduce a saturation modal gain of 6 cm^{-1} and a transparency current density of 10 A/cm^2. This value is very close to a simple estimate of the transparency current density,

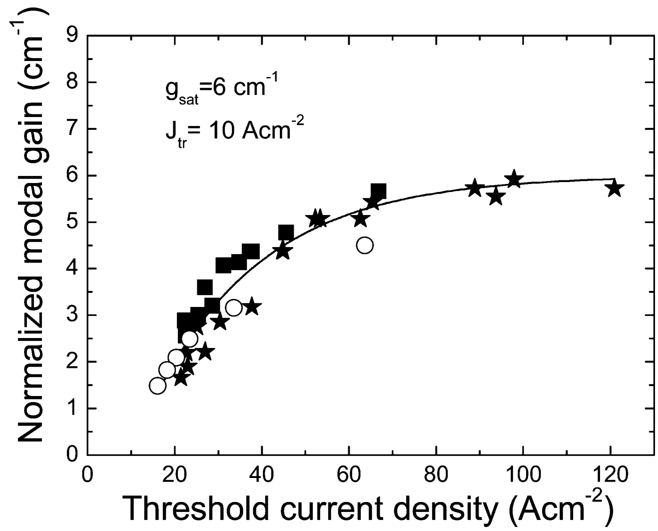

Fig. 8. Modal gain versus threshold current density at room temperature normalized to one QD layer.

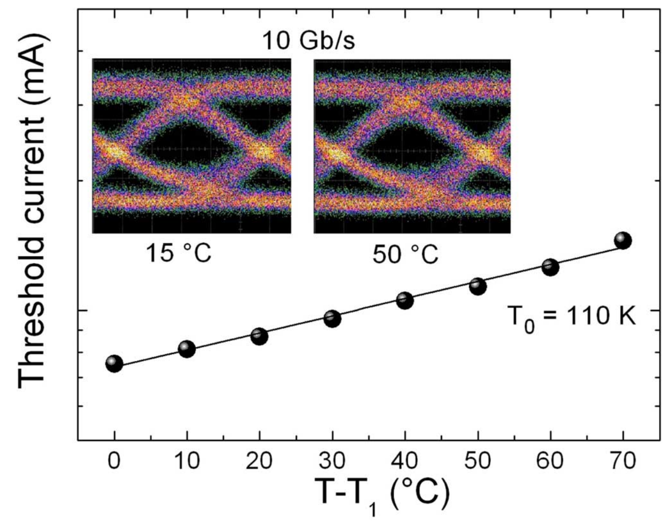

Fig. 10. Threshold current density versus temperature of a single-mode device containing six QD layers. The inset shows 10 Gb/s eye diagrams at 15 °C and 50 °C.

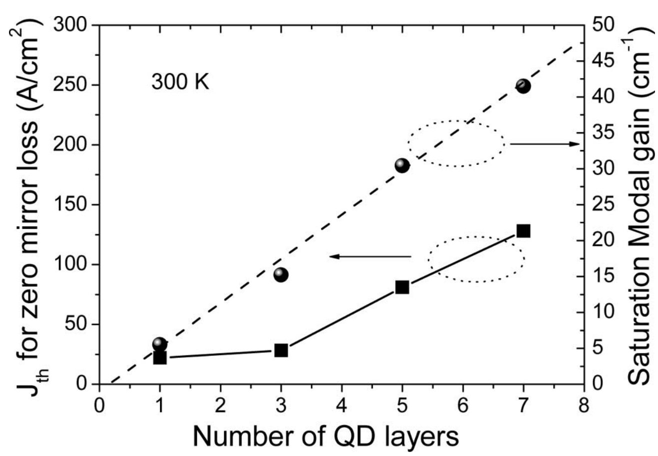

Fig. 9. Threshold current density for an infinite cavity length and saturation modal gain at room temperature as a function of the number of QD layers.

which corresponds to radiative recombination via the ground state ($J_{\rm tr} = {\rm eN_s}/\tau_{\rm r}$ in which $\tau_{\rm r}$ is the radiative lifetime ~0.5 ns, N_s the QDs surface density $\sim 4 \times 10^{10}$ cm^{-2} [31], [32]). To evaluate the material gain, it is necessary to calculate the QDs confinement factor $\Gamma_{\rm QDs}$ expressed by

$$\Gamma_{\rm QDs} = \Gamma_z f \tag{2}$$

where Γ_z is the overlap of the QDs and the optical field along the growth direction and f is the fractional occupancy of the QDs. For the present structure with a single layer of QD, $\Gamma_z = 1.233 \times 10^{-2}$ and $f = 7.06 \times 10^{-2}$, which gives $\Gamma_{\rm QDs} = 8.7 \times 10^{-4}$ and the material gain $G^{\rm mat}_{\rm QDs} = 6892$ cm^{-1} at room temperature.

Fig. 9 shows the threshold current densities for an infinite cavity length and the saturation modal gain for the four laser structures as a function of the stack number. The threshold current density is proportional to the QD number in all the laser structures. A linear increase of $J_{\rm th}$ should be observed because in a single QD, only two carriers can occupy the ground state (Pauli's principle). The extracted threshold current densities for an infinite cavity length are 22 A/cm^2, 28 A/cm^2, 86 A/cm^2, and 128 A/cm^2 for the laser structures having one, three, five, and sevem QD layers, respectively. The threshold current density increases but not linearly with the number of QD layers; this behavior could be attributed to the increase of nonradiative recombination processes in the QD lasers having a higher number of QD layers. The saturation modal gain linearly increases with the number of QD layers with a rate of 6 cm^{-1} per QD layer. This demonstrates that the stacking procedure does not alter the optical properties of the QDs.

Exploiting the high modal gain of the examined QDs, we have fabricated single-mode devices to test the direct modulation characteristics. A laser structure containing six QD layers was grown and processed into single-mode devices. We note that in the case of this structure, the selective p-doping to spacer layers was not introduced. Moreover, in order to improve both the static and dynamic characteristics, we applied high-reflection (HR) coatings (50%–80%) on the cleaved facets of the shortest devices. In fact, higher reflections allow lower threshold currents, limit losses, and also make easier lasing from a very short cavity where the photon lifetime is shorter and parasitic effects are limited. Fig. 10 shows the threshold current as a function of T–T_1 (where T is the temperature and $T_1 = 15\,^\circ$C) of an HR-coated 2-μm-wide and 600-μm-long cavity in a wide temperature range (15 °C–85 °C). Such measurements were carried out in a continuous wave operation. The lasing wavelengths were 1.29 μm at 15 °C and 1.34 μm at 85 °C and the laser operates at the ground state in the whole range of temperature. The characteristic temperature T_0 of the device is 110 K, which is among the highest characteristic temperatures reported so far for 1.3-μm InAs QD lasers, without p-doping of the active region.

The saturation modal gain of the ground state of this laser structure was ~36 cm^{-1}, which is in good agreement with the variation of the modal gain with the number of layers reported previously. Direct modulation measurements at high repetition rates were also performed. The inset of Fig. 10 shows eye pattern diagrams at 10 Gb/s. A clear eye opening at 15 °C and 50 °C with an extinction ratio of 5 dB was obtained [33]. Such a high-frequency modulation can be related to the fast carrier relaxation process observed in these QD samples and described in Section III.

V. Summary

In this study, we analyzed a wide range of issues concerning 1.3-μm QD lasers. A linear increase of the saturation modal gain with the number of QD layers was obtained reaching a value as high as ∼42 cm^{-1} in QD laser devices containing seven QD layers. The achievement was associated to the optimization of the growth parameters in order to preserve the optical properties of QDs during the stacking procedure. A low transparency current density per QD layer of 10 A/cm^2 was obtained in all laser structures, which is very close to the calculated one. Exploiting the high modal gain, the fabrication of a single-mode device allows the demonstration of 10-Gb/s direct modulation at 15 °C and 50 °C. This high-frequency modulation can be associated to the particular carrier dynamics demonstrated by time-resolved spectroscopy and absorption measurements. In addition, a high characteristic temperature of 110 K was obtained in a large temperature range.

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