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Comparison of radiative and structural properties of 1.3 μm $In_xGa_{(1-x)}As$ quantum-dot laser structures grown by metalorganic chemical vapor deposition and molecular-beam epitaxy: Effect on the lasing properties

A. Passaseo,[a] M. De Vittorio, M. T. Todaro, I. Tarantini, M. De Giorgi, and R. Cingolani
National Nanotechnology Laboratory, INFM-Unità di Lecce c/o Dipartimento di Ingegneria dell'Innovazione, Università di Lecce, Via Arnesano, 73100 Lecce, Italy

A. Taurino and M. Catalano
Consiglio Nazionale delle Ricerche, Istituto IMM-CNR, via Arnesano, 73100 Lecce, Italy

A. Fiore,[b] A. Markus, J. X. Chen, C. Paranthoen, U. Oesterle, and M. Ilegems
Institute of Quantum Electronics and Photonics, Ecole Polytecnic Fédérale de Lausanne (EPFL), CH-1015 Lausanne, Switzerland

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We have studied the radiative and structural properties of identical $In_xGa_{(1-x)}As$ quantum dot laser structures grown by metalorganic chemical vapor deposition (MOCVD) and molecular beam epitaxy (MBE). Despite the comparable emission properties found in the two devices by photoluminescence, electroluminescence, and photocurrent spectroscopy, efficient lasing from the ground state is achieved only in the MBE sample, whereas excited state lasing is obtained in the MOCVD device. Such a difference is ascribed to the existence of the internal dipole field in the MOCVD structure, induced by the strong faceting of the dots, as observed by high-resolution transmission electron microscopy.
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InGaAs/GaAs self-assembled quantum dots (QDs) are attracting considerable interest due to their zero-dimensional properties and their potential for device applications. Lasers emitting at room temperature in the 1.3 μm region and with a low threshold current have been demonstrated by molecular beam epitaxy (MBE).[1–4] However, so far there have been no reports on lasing in 1.3 μm from QD laser structures grown by metalorganic chemical vapor deposition (MOCVD). Only a few works have shown luminescence and electroluminescence at 1.3 μm in QDs fabricated by MOCVD.[5–7]

A variety of theoretical[8] and experimental[9] studies have recently reported the existence of a permanent electron-hole dipole moment in a QD, which is related to the built-in strain field inside the dots. The permanent dipole is sensitive to the detailed structure of the dots, which is strictly related to the growth conditions. In our previous work[7] we demonstrated the existence of a large dipole moment in our MOCVD grown QD lasers, which strongly influences the emission spectra.

In this letter we investigate the structural and optical properties of identical QD laser structures grown by MOCVD and MBE, emitting in the spectral range around 1.3 μm. More specifically, we show that the different shape of the dots [truncated pyramid in the MOCVD samples, lens-shape in MBE samples] results a larger built-in dipole field in the MOCVD samples. The strong piezoelectric field associated to the (111) lateral surface, developed with the self-organized growth, strongly enhance the effect of the internal dipole field, related to the built-in strain field and compositional profile. Therefore, even though the photoluminescence (PL) spectra from the MBE and the MOCVD samples are identical, the MBE devices exhibit efficient ground state lasing, whereas the MOCVD devices exhibit only excited state lasing.

The investigated samples consist of in-plane laser structures grown on $(100)n^+$ doped GaAs substrates, containing a single QD active layer. A detailed description of the samples is reported elsewhere.[6,10] The MBE QDs were grown by depositing 2.9 MLs of InAs at the growth rate of 0.13 ML/s and at a substrate temperature of 530 °C on GaAs. The dots were subsequently covered by 7-nm-thick $In_{0.15}Ga_{0.85}As$ layer to shift the emission wavelength up to 1.3 μm.[11]

The areal QD density and uniformity of the QDs layers was investigated by atomic force microscopy (AFM) and by plan-view TEM micrograph (not shown here). In both samples the areal QDs density was found to be about 3×10^{10} cm^{-2}, with a comparable size dispersion (lower than 7%). Cross-sectional samples were investigated by using a JEOL 4000 EX transmission electron microscope, operating at 400 kV accelerating voltage. The optical characterization of the samples was performed by photoluminescence measurements (PL) in a temperature range between 10 and 300 K. Electroluminescence (EL) and photocurrent (PC) experiemental conditions are described in Refs. 7 and 12.

Figure 1 shows the RT PL spectra recorded at low excitation intensity for the MOCVD and MBE sample. Both samples exhibit a sharp peak around 1.3 μm with comparable full width at half maximum (around 27 meV for the

[a] Author to whom correspondence should be addressed; electronic mail: adriana.passaseo@unile.it
[b] Permanent address: Institute of Photonics and Nanotechnology, CNR, via del Cineto Romano 42, 00156 Roma, Italy.

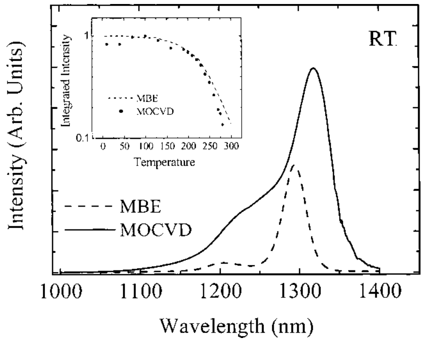

FIG. 1. Room temperature PL spectra recorded at low excitation intensity of the MOCVD (solid line) and MBE sample (dashed line). Inset: temperature dependence of the PL integrated intensity for the two samples.

MOCVD sample and 24 meV for the MBE sample) Comparable results are also obtained by analyzing the temperature dependence of the PL integrated intensity of the two samples (shown in the inset of Fig. 1), and the PL intensity as a function of the excitation power (not shown). The room temperature radiative efficiency of the two samples decreases only by a factor 7 between 10 and 300 K and the integrated intensity remains nearly constant for both samples in the range of 10 K$<T<$150 K. Nonradiative recombination becomes important only above 150 K.

Despite the comparable distribution and optical properties of the dots suggests that both samples are suitable candidates for laser application, the dots exhibit a different behavior when they are inserted in a laser structure, where the energetic states are affected by the internal electric field.

Figures 2(a) and 2(b) show the room temperature PL, EL, and PC spectra of the QD samples, grown by MOCVD and MBE, respectively. The ground state PL of the MOCVD sample occurs at the designed wavelength (above 1.3 μm),

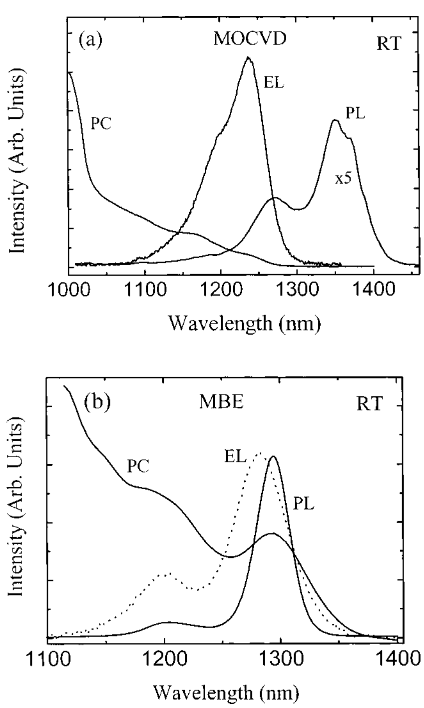

FIG. 2. Room temperature PL emission compared with and EL and PC spectra of the QD MOCVD grown structure (a) and MBE grown structure (b).

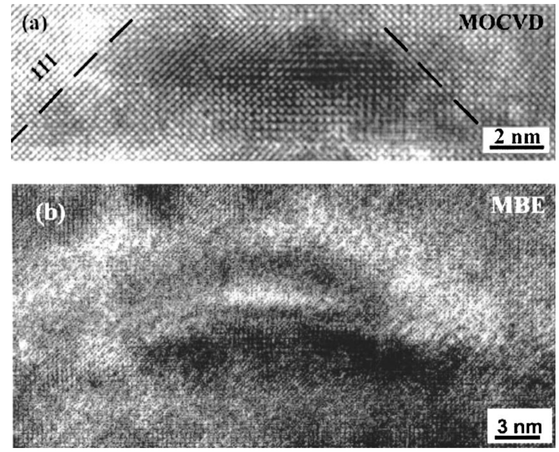

FIG. 3. Cross-sectional HRTEM micrograph of QD samples grown by MOCVD (a) and MBE (b). The (111) sidewalls of the MOCVD QD are evidenced.

as shown by Fig. 2(a), but the EL peak, which corresponds to the first excited state, is shifted to lower wavelength, up to 1242 nm in this sample. The PC measurements performed without bias confirm the absence of the ground state resonance, showing measurable absorption only at the energy of the first excited state. On the contrary, the EL emission of the MBE sample shows only a moderate shift (around 15 nm) with respect to the PL ground state energy position [centered around 1300 nm, Fig. 2(b)]. Consistently, the PC spectrum exhibits a clear ground state resonance at 1.3 μm and the excited state absorption peak at higher energies.

As described in Ref. 7, we explain the strong blueshift occurring in the MOCVD sample by the existence of a large permanent electron-hole (e–h) dipole, which separates spatially the ground state wave functions of the hole and of the electron. We want to point out that the limited height of the dots (3–5 nm) is not enough to reduce the ground state e–h overlap substantially, even at very strong fields. The in-plane separation of the e–h wave functions should be invoked to explain the observed reduction of the ground level emission and photocurrent. To confirm this hypothesis we need a full three-dimensional map of the electric field in the dots (without separating the z and xy components). This study is currently in progress, and will be the subject of a forthcoming article. However, it has been demonstrated[8] that the direction and the strength of the permanent dipole moment depend on the shape and on the composition profile of the QDs. As a consequence, the different behavior found in the MBE- and MOCVD-grown samples should be related to microstructural differences of the QDs grown with the different techniques.

In Fig. 3 we show the cross-sectional HRTEM micrograph of QD samples grown by MOCVD [Fig. 3(a)] and MBE [Fig. 3(b)], respectively. The first remarkable difference between the two samples is that the MOCVD sample shows a truncated pyramidal shape and a strong faceting, whereas the MBE sample exhibits a disk shape, without evident faceting. The precise dimensions could not be determined with high accuracy because the complex image contrast is affected by strain, composition, and sample thickness. However, the images clearly show a larger lateral extension (around 30 nm) for the MBE QD as compared to the MOCVD QDs (around 15 nm). Despite this larger basis, the

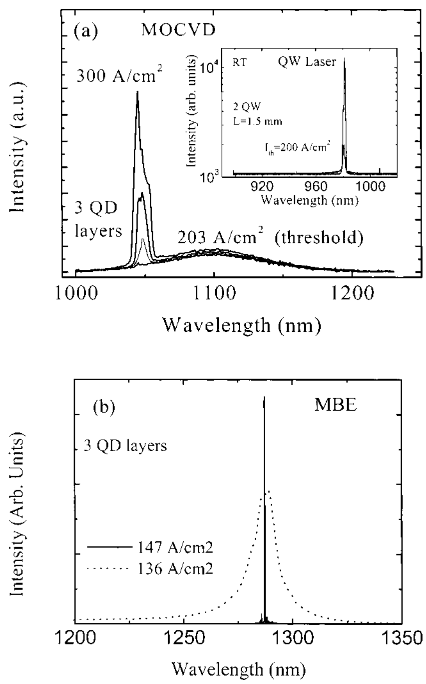

FIG. 4. Laser emission of QD devices containing three QD layers as active material, grown by MOCVD (a) and MBE (b). Lasing from the ground state is obtained in the MBE sample at room temperature, for a device length of 2 mm. Inset: laser emission of QWs device; the active layer consists of two $In_{0.17}Ga_{0.83}As$ quantum wells 8 nm thick.

MBE QDs do not have a proportionally larger height (around 4–4.5 nm for MBE and 3–3.5 for MOCVD), resulting in a height to base ratio (h/b) roughly half of the corresponding ratio in the MOCVD samples, as confirmed by AFM observations. The lower h/b ratio obtained by the MBE growth technique is probably a consequence of the slower growth rate employed for the growth of the QDs, which results in larger island size,[10,12] and/or of the stronger interdiffusion[13,14] of In in the barrier, which reduces the dot height and smears out the dot interfaces. However, the higher QDs h/b ratio obtained with the MOCVD growth leads to the appearance of well defined (111) lateral sidewalls, which generate strong piezoelectric fields. The components of this fields parallel to the growth direction reinforce the strength of dipole field associated with the built-in strain field, which is directed from the base of the dots to their apex.[8,9]

Due to the lower h/b ratio, in the MBE sample the lower interface is connected to the upper interface with different high index surface of small extension, with a reduced piezoelectric field.

The stronger influence of the internal fields in the QDs MOCVD grown samples is dramatically reflected in the laser emission of the structures. In Fig. 4, we compare laser devices containing three QD layers as active material, grown by MOCVD [Fig. 4(a)] and MBE [Fig. 4(b)], respectively. Due to the combined effect of the piezoelectric field with the internal dipole field, in the MOCVD structure lasing action is achieved only from the excited states, even in relatively long devices, the ground state population being completely depleted by the internal fields (piezoelectric, dipole and junction field).[7] On the contrary, ground state lasing at around 1.3 μm at room temperature is observed from the MBE[15,16] sample for device length of 2 mm and threshold current density of 140 A/cm^2. The lack of ground state lasing in the MOCVD sample is not related to higher cavity losses or processing problems. In order to verify the quality of the MOCVD growth and laser device processing, a test process has been performed on two identical devices, embedding two InGaAs/InGaAs quantum dots layers or two $In_{0.17}Ga_{0.83}As$ quantum wells 8 nm thick, designed to have the ground state emission at 980 nm. Lasing from the quantum wells samples has been easily obtained at 980 nm with a current threshold below 200 A/cm^2, [inset of Fig. 4(a)] comparable to state of the art results in literature.

In conclusion, temperature dependent photoluminescence, electroluminescence, and photocurrent spectroscopy were employed to compare the optical properties of identical QD laser structures emitting at 1.3 μm, grown by MOCVD and MBE. Despite both structures exhibit comparable spectra, efficient lasing from the ground state is obtained only in the MBE sample. In the MOCVD laser structure the existence of a larger built-in dipole field prevents lasing from the ground state, allowing emission only from the excited states. The stronger electric field in the MOCVD sample is associated to well defined (111) sidewalls, evidenced by HRTEM, whose piezoelectric field adds to the internal dipole field, induced by the built-in strain field and compositional profile.

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