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Wavelength Tunable (1.55 μm Region) InAs/InGaAsP/InP (100) Quantum Dots in Telecom Laser Applications

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1. Introduction

At SSDM 2004 we have reported wavelength tunable (1.55 μm region) InAs/InGaAsP/InP (100) quantum dots (QDs) grown by chemical beam epitaxy (CBE) [1]. Wavelength tuning was achieved through insertion of ultrathin GaAs interlayers underneath the QDs. The GaAs interlayers reproducibly control the As/P exchange during InAs growth to continuously reduce the QD height as a function of interlayer thickness and, hence, the QD emission wavelength. Here we report the realization of wavelength tunable InAs/InGaAsP/InP (100) QDs grown by metal organic vapor-phase epitaxy (MOVPE) and their applications in QD lasers operating in the 1.55 μm region for telecom applications. Once growth conditions such as growth temperature, gas switching sequence, and group V-III flow ratio are optimized, the QD wavelength tuning upon GaAs interlayer thickness is as effective in MOVPE as in CBE [2]. Narrow-ridge waveguide lasers with such wavelength tunable QDs as active region operate at room temperature (RT) in continuous wave (cw) mode on the QD ground state transition.

2. Experimental Details

The samples were grown by MOVPE using TMI, TMG, TBA, and TBP as gas sources. InAs QDs plus GaAs interlayers (1-2 MLs) underneath were placed in the center of a lattice-matched InGaAsP layer with bandgap at 1.25 μm (Q1.25) grown at 500 ºC. The nominal amount of InAs was 3 and 3.5 MLs. The QDs were stacked in up to five layers. The thickness of the Q1.25 waveguide core of the laser structure was 500 nm, and the bottom and top claddings were 500 nm n-InP buffer on n-InP substrate and 1.5 μm p-InP completed by a compositionally graded p-InGaAsP contact layer.

3. QD Properties

Figure 1 shows the RT photoluminescence (PL) spectra of the three-fold widely-stacked InAs QDs with Q1.25 separation layers of 40 nm thickness. The InAs amount is 3 MLs. The QD peak wavelength is continuously blue-shifted with increasing GaAs interlayer thickness due to reduced QD height, shown in the atomic force microscopy (AFM) images in Fig. 2, confirming the suppression of As/P exchange. The wavelength reduction coincides with that of single QD layers, revealing the reproduction of identical QDs upon stacking to increase the active volume [3]. On the other hand, QD layers separated by only 4 nm Q1.25 exhibit a red shift of the PL peak of about 90 nm. This indicates vertical electronic coupling of these closely-stacked QDs which is proven by the linear polarization of the cleaved-side PL changing from in plane to isotropic – highly demanded for polarization independent semiconductor optical amplifiers (SOAs).

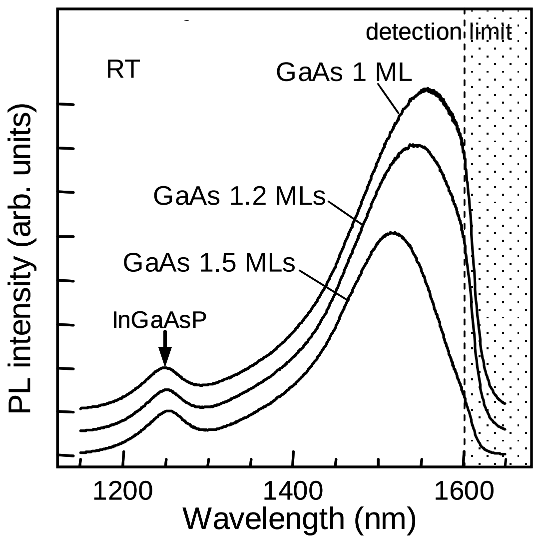

Fig. 1 RT PL spectra of the three-fold widely-stacked 3-MLs InAs QDs with different GaAs interlayer thickness. The detection limit of the cooled InGaAs detector is at 1.6 μm.

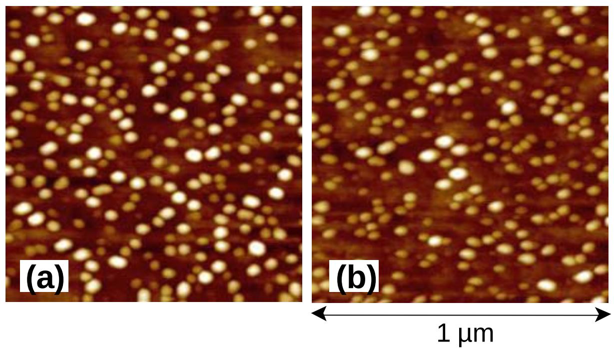

Fig. 2 AFM images of the 3-MLs InAs QDs on the surface with GaAs interlayer thickness of (a) 1.2 and (b) 2.0 MLs. The height contrast is 10 nm. The average QD height decreases from 5.6 nm for 1.2 MLs GaAs to 4.5 nm for 2 MLs GaAs.

4. QD Laser

The laser structure is processed into narrow-ridge waveguides with 3.5 µm width and cavity length between 1 and 3.6 mm. Before metallization, the waveguides are planarized by polyimide. The active region is composed of five-fold widely-stacked InAs QDs (3.5 MLs InAs, 1 ML GaAs, 40 nm Q1.25 separation layers) with RT PL peak wavelength and line width of 1.58 µm and 110 meV. A cross-sectional scanning electron microscopy (SEM) image is shown in Fig. 3.

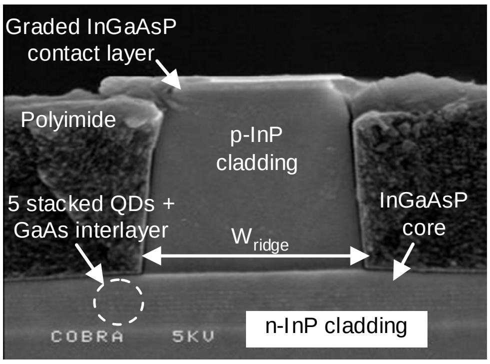

Fig. 3 Cross-sectional SEM image of the QD laser structure.

The electroluminescence (EL) and lasing spectra taken from the as-cleaved facet of the QD lasers with 1 and 3.6 mm cavity length are shown in Fig. 4. Measurements are performed at RT in cw mode. For the 1-mm long device, the lasing wavelength and threshold current I_{th} are 1.57 µm and 125 mA, corresponding to a threshold current density, J_{th}, of 3.6 kA/cm^2. J_{th} is reduced to 1 kA/cm^2 for 3.6 mm cavity length owing to the lower relative mirror loss, and the lasing wavelength is increased to 1.65 µm.

The red-shift of the lasing wavelength with increasing cavity length is attributed to the QD size distribution. For long devices, lower density, larger QDs with emission at the long-wavelength side of the PL spectrum already support lasing. For shorter devices, higher density, smaller QDs with shorter emission wavelengths toward the PL peak are required. Lasing occurs on the QD ground state transition. This is proven by simultaneous ground-state and excited-state lasing at larger currents, which is observed under pulsed conditions.

J_{th} under pulsed conditions is generally lower than that measured in cw mode due to suppression of heating. The minimum J_{th} is 580 A/cm^2 for the 3.6-mm long device. Extrapolation of the linear dependence of J_{th} on the inverse cavity length to zero yields an ultra-low transparency current density of 30 A/cm^2, i.e., 6 A/cm^2 per QD layer. The total external differential quantum efficiency determined from the light output power versus current curves reveals an internal loss of 4.2 cm^{-1} and an internal differential quantum efficiency of 37 %. The maximum achievable QD ground state modal gain is estimated to be 14.7 cm^{-1} at 1.57 µm from the 1-mm long device. This takes into account the mirror reflectivity of 0.35 and the fact that devices shorter than 1 mm lase on the excited state due to ground state gain saturation. These values together are among the best achieved for InAs/InP (100) QD lasers operating in the 1.55 µm wavelength region for applications in optical telecommunication systems [4].

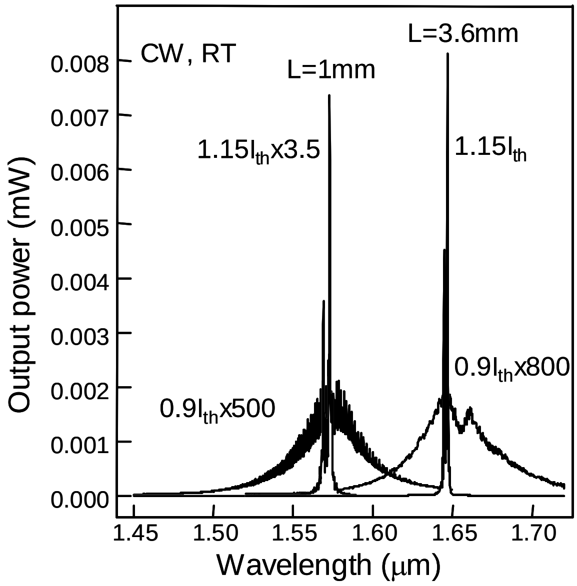

Fig. 4 EL and lasing spectra taken at RT in cw mode of the ridge-waveguide QD lasers with cavity length L of 1 and 3.6 mm.

5. Conclusions

Wavelength tuning of MOVPE grown InAs/InGaAsP/InP (100) QDs over the 1.55 µm region has been achieved through insertion of ultrathin GaAs interlayers underneath the QDs. QD lasers employing such wavelength tunable QDs, stacked in growth direction, operate at room temperature in continuous wave mode on the QD ground state transition with excellent device performance ready for telecom applications.

Acknowledgements

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References

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