Low threshold current density 1.3 µm InAs/InGaAs quantum dot lasers with InGaP cladding layers grown by gas-source molecular-beam epitaxy

F.Y. Chang, J.D. Lee and H.H. Lin

InAs/InGaAs quantum dot lasers with InGaP cladding layers grown by gas-source molecular-beam epitaxy are reported. The laser emits 1.296 µm light output and demonstrates a very low threshold current density of 111 A/cm^2. This is the lowest reported value of GaAs-based 1.3 µm quantum dot lasers with InGaP cladding layers.

Introduction: 1.3 µm In(Ga)As quantum dot (QD) lasers grown on GaAs substrate are promising candidates for GaAs-based long-wavelength diode lasers [1–3], which will be the key light sources for fibre optical communication systems. Recently, a number of significant improvements in the performance of QD lasers, including low threshold current density, room temperature continuous-wave (CW) operation, and high characteristic temperature (T_0), have been reported [1, 2]. However, in contrast to most studies on QD lasers with AlGaAs cladding layers, very few studies have shown the long-wavelength lasing of QD lasers with InGaP cladding layers [3, 4]. InGaP has lower reactivity with carbon and oxygen, lower surface-recombination velocity, and lower deep trap concentration [5, 6], compared with AlGaAs. Furthermore, its growth temperature is also compatible with QD. In this Letter, we report the ground-state lasing of InAs/InGaAs QD lasers with InGaP cladding layers grown by gas-source molecular-beam epitaxy (MBE). For an as-cleaved laser with a cavity length of 3.02 mm, the lasing wavelength is 1.296 µm and the threshold current density is 111 A/cm^2 at room temperature, which is the lowest value so far reported in Al-free GaAs-based lasers at 1.3 µm wavelength range.

Device structures and growth: The laser structure was grown by gas-source MBE on a (100) n^+-GaAs substrate. Fig. 1 is a schematic illustration of fabricated QD lasers. The laser structure consists of a 500 nm-thick n-type GaAs buffer layer, a 1.7 µm-thick n-type $In_{0.49}Ga_{0.51}P$ lower cladding layer with doping concentration from 2×10^{18} to 5×10^{17} cm^{-3}, a 200 nm-thick GaAs waveguide layer in which the QD active medium is embedded, a 1.6 µm-thick p-type $In_{0.49}Ga_{0.51}P$ upper cladding layer with doping concentration from 1×10^{17} to 5×10^{18} cm^{-3}, and a 200 nm-thick heavily Be-doped (1.5×10^{19} cm^{-3}) GaAs contact layer. In the centre of the waveguide are triple stacks of QD layers. For growing each QD layer, 2.3 ML InAs was deposited first, followed by a 9.0 ML $In_{0.33}Ga_{0.67}As$ capping layer. The high composition of InGaAs capping layer was grown by the GaAs/InAs sequential binary growth method, as described in [3]. Between the QD layers are 25 nm-thick GaAs spacers. The growth temperatures of InAs QDs, InGaAs capping layers and InGaP cladding layers were 535°C, 480°C, and 460°C, respectively. The density of each QD layer was 4.5×10^{10} cm^{-2}. After capping the InAs QDs with InGaAs layer and 6-nm-thick GaAs, the temperature was raised to 590°C to eliminate the dislocation, which may occur with the formation of QDs [7].

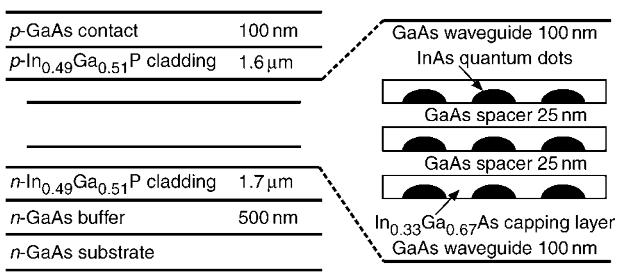

Fig. 1 *Schematic illustration of QD laser containing triple stacks of InAs QDs with InGaAs capping layer and InGaP cladding layers*

Room temperature photoluminescence (PL) results are shown in Fig. 2. The PL was measured after the GaAs contact layer and the InGaP cladding layer were removed. The PL linewidth of the ground state is 29 meV, indicating good homogeneity of QDs, and is better than that in [3] because of high growth temperature of InAs QDs. Since the higher growth temperature gives rise to a narrower size distribution of QDs [8] and In–Ga intermixing can be suppressed during the overgrowth of the InGaAs capping layer at low growth temperature [9], both result in a narrower PL linewidth.

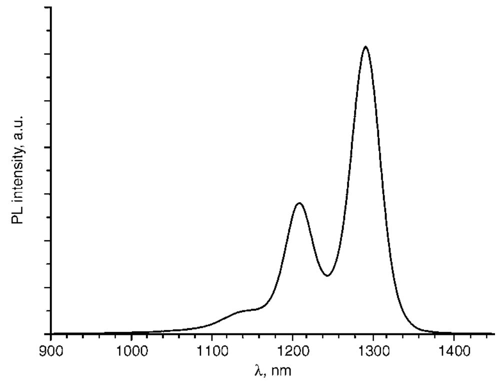

Fig. 2 *Photoluminescence spectrum of QD laser*

FWHM is 29 meV

Characteristics of the laser: Broad area lasers with 50 µm stripe width were fabricated from the structure. The wafer was cleaved with different cavity lengths, and the fabricated lasers were tested under pulsed mode with a pulse width of 4 µs and a repetition rate of 500 Hz. Fig. 3 shows the single-facet output L–I curve from a typical bar with cavity length of 3.02 mm. The threshold current density is 168 mA, which corresponds to the threshold current density of 111 A/cm^2. The external quantum efficiency is 39%. Fig. 4 shows electroluminescence (EL) spectra taken from the QD lasers with different cavity lengths by using an optical spectrum analyser (OSA). The lasing wavelength of 3.02 mm-long lasers is 1.296 µm, corresponding to the ground-state transition. For the lasers with cavity length of 0.96 and 0.56 mm, the emission lines are at 1.208 and 1.135 µm, associated with the first excited state and second excited state, respectively. The lasing states of the QD lasers are dependent on the cavity length. The linear dependence of the inverse external quantum efficiency on the cavity length is shown in Fig. 5, from which the internal quantum efficiency of 68% and the internal loss of 2.9 cm^{-1} are deduced. Using the condition that the gain is equal to the total losses (cavity and mirror) on the laser with 1.04 mm-long cavity, which is the shortest cavity length capable of ground state lasing, we can determine that the saturation gain of the ground state is 13.9 cm^{-1}.

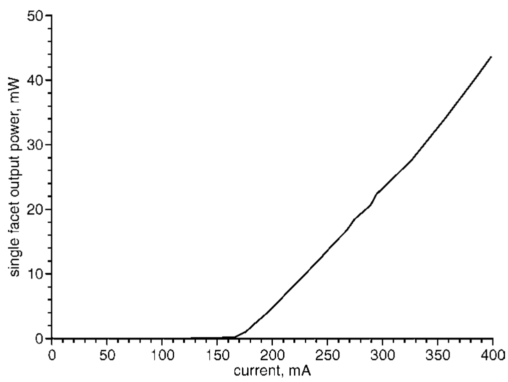

Fig. 3 *Single facet output L–I curve of 3.02 mm cavity length laser with* $J_{th} = 111$ A/cm^2 *and* $\eta_d = 39\%$

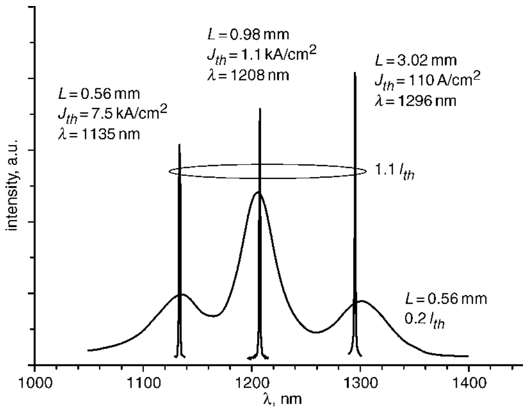

Fig. 4 *Electroluminescence spectra taken from QD lasers with different cavity lengths*

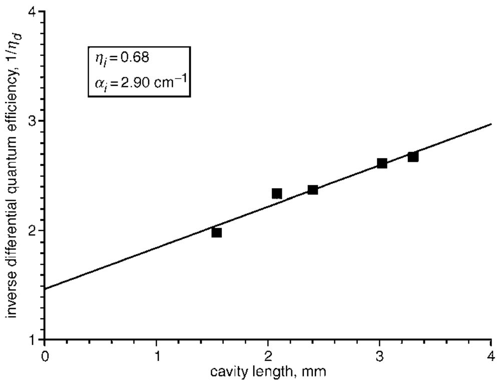

Fig. 5 *Cavity length dependence of inverse external quantum efficiency*

Conclusions: We have successfully grown a low threshold current density InAs/InGaAs QD laser with InGaP cladding layers by using gas-source MBE. Ground-state lasing at RT with a low threshold current density of 111 A/cm^2 has been achieved at a wavelength of 1.296 μm. Internal quantum efficiency of 68% and internal loss of 2.9 cm^{-1} are obtained. The saturation gain of the ground state at RT is estimated to be 13.9 cm^{-1}. The low threshold current density and high ground-state saturation gain is attributed to the good homogeneity of QDs.

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