Low-threshold current density InAs quantum dash lasers on InP (100) grown by molecular beam epitaxy

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Low-threshold current density InAs quantum dash lasers are demonstrated by reducing the energy inhomogeneous broadening through an optimised double-cap technique. A threshold current density for an infinite cavity length of 225 A/cm^2 (~45 A/cm^2 per stack) is obtained from a five-stack laser structure. The characteristic temperature above room temperature is 52K, and this relatively low value results from the carrier leakage from the dash into the barrier (waveguide) region.

Introduction: Self-assembled quantum dash (QDH) and quantum dot (QD) lasers are expected to have a superior performance, such as low threshold current density (J_{th}), high temperature stability, high modulation bandwidth, and ultrafast operation [1–5]. These are based on their unique properties of discrete atomic-like energy levels. However, owing to the inhomogeneous broadening of practical QDHs (QDs), some interesting features are limited. Long wavelength self-assembled InAs QDHs grown on InP substrates have been explored to obtain wavelength emissions of 1.55 μm for optical fibre communications, but the typical PL linewidth of InAs/InP QDHs is more than 100 meV, much larger than that of the InAs/GaAs material system and even larger than that of the QD structures for the same material system, resulting from the difficulty to control the As/P exchange [6]. The double-cap technique has therefore been developed to control the As/P exchange during QDH formation, with successful tuning of the emission wavelength into the range of 1.55 μm. To obtain a low J_{th} performance, multiple stacks of layers are generally used to increase the modal gain, which is proportional to the stack number, resulting from the increase of the optical confinement factor. In this Letter, we report room-temperature operation InAs QDH lasers on InP substrates with InGaAsP as optical waveguides, emitting at around 1.58 μm. A low-threshold current density for an infinite length of 225 A/cm^2 is obtained. Internal quantum efficiency and internal optical loss are deduced to be 55% and 7 cm^{-1}, respectively. The characteristic temperature (T_0) is measured to be 55K above room temperature.

Experiments: The QDH laser structures were grown by molecular beam epitaxy (MBE) on an *n*-doped InP (100) substrate. The laser structure is based on a separate confinement waveguide design consisting of a 320 nm-thick $In_{0.8}Ga_{0.2}As_{0.43}P_{0.57}$ (Q1.18) lattice matched to an InP substrate. The lower cladding consists of an InP substrate and a 600 nm-thick InP layer. The upper cladding and contact layers are 2000 nm-thick InP and 200 nm $In_{0.53}Ga_{0.47}As$, respectively. In the centre of the waveguide core, the QDH active region consists of a five stacked 2.1 MLs InAs dash layer with 20 nm Q1.18 as spacer layers. Importantly, after the formation of QDs, a first cap of 2.2 nm-thick Q1.18 is deposited, and then 30s growth interruption under $As_2 + P_2$ flux is optimised. After that the rest spacer layer of Q1.18 is deposited for completion, i.e. the double-cap technique [6]. The growth temperature for the entire structure was kept at 480°C. Rapid thermal annealing (RTA) has been performed at 360°C to improve the alloy quality.

The dash is preferentially elongated along the [01-1] direction. Broad-area lasers were fabricated by a standard technique. The laser stripe is patterned perpendicular to the dash direction to obtain higher gain [7]. Cavities with various lengths and both facets uncoated were tested at room temperature (RT) through pulsed current injection (500 ns pulse width and 2 kHz repetition). The laser exhibits a turn-on voltage of 0.7 V.

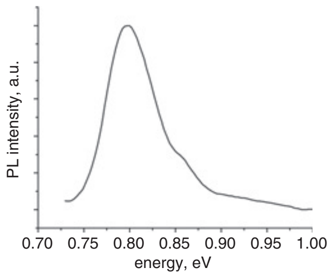

Fig. 1 *PL spectrum taken at RT of five-stack QDH structure*

Results: Fig. 1 shows the PL spectrum obtained at RT for a five-stack QDH. With this optimised double-cap growth condition, the result shows the peak energy at 0.797 eV (corresponding to a wavelength of 1.56 μm) and a narrow full width at half maximum (FWHM) of 60 meV, which is much lower than the typical value of 100 meV for conventional methods, indicating a small energy inhomogeneous broadening.

Fig. 2 shows the J_{th} exponential dependency on the inverse cavity length. The current density for an infinite length of 225 A/cm^2 is derived for the five-stacked QDH laser, i.e. 45 A/cm^2 per QDH layer. This low value for QDH lasers indicates their potential to reach an ultra-low threshold and thus ultrafast operation as well in the future. The inset corresponds to the lasing spectrum under an injection current density of 1.1 × J_{th} for a cavity length of 1.2 mm. The lasing wavelength is centred at 1.587 μm, in accordance to the PL emission wavelength, confirming that the lasing is at ground state.

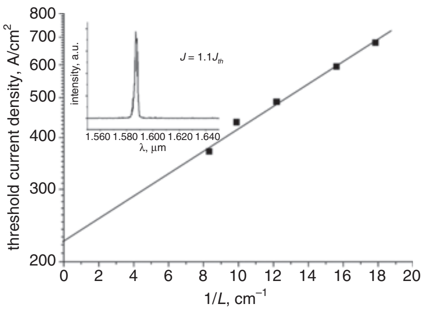

Fig. 2 *J_{th} against reciprocal length taken at RT for five-layer stacked QDH lasers*

Inset: Lasing spectrum at 1.1 × J_{th} for cavity length of 1.2 mm

From the light–current (L–I) characteristics for these optimised laser structures, the inverse external quantum efficiency ($1/\eta_{ext}$) as a function of the cavity length is shown in Fig. 3. The internal quantum efficiency (η_{int}) and internal optical loss (α_{int}) are extracted to be 55% and 7 cm^{-1}, respectively. The value of α_{int} is comparable to those reported for QD lasers (4–10 cm^{-1}) [5], which is lower than the typical values of 10–20 cm^{-1} reported for QDH lasers [1]. This is believed to be a reflection of the material quality improvement through the optimised double-cap technique, confirmed also by the small PL linewidth from Fig. 1. Therefore, the less energy dispersion and the lower α_{int} result in a lower threshold current in the QDH laser compared to the previously grown structure [8], since the lower pumping level is reached for enough modal gain.

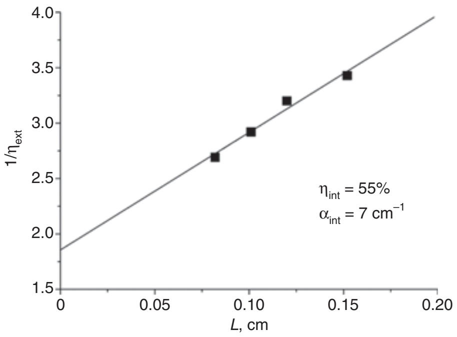

Fig. 3 *Inverse external quantum efficiency against cavity length taken at RT*

The temperature dependence of J_{th} is shown in Fig. 4 in the range 25–70°C. The characteristic temperature of the threshold (T_0) is determined to be 52K. The relatively low T_0 originated from the low energy confinement from the Q1.18 waveguide and the low band offset ratio for the conduction band [1, 9, 10].

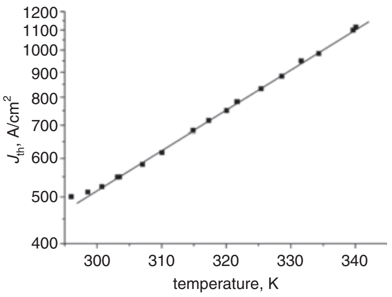

Fig. 4 *J_{th} against temperature for five-stack QDH laser*

Conclusions: We have demonstrated a quantum dash laser emitting at 1.58 μm grown by the gas source MBE. Broad-area lasers show a low-threshold current density for an infinite length of 225 A/cm^2 (45 A/cm^2 per dash layer). It results from the small energy inhomogeneous broadening and low internal optical loss. The characteristic temperature of 52K is deduced in the temperature range 25–70°C.

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