SEMICONDUCTOR AND INTEGRATED OPTOELECTRONICS (SIOE)

Demonstration of 1.51 μm InAs/InP(3 1 1)B quantum dot single-mode laser operating under continuous wave

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Abstract: The achievement of a 1.51 μm InAs/InP(3 1 1)B quantum dot (QD) single-mode Fabry–Perot laser operating under continuous wave at room temperature is reported. A threshold current of 80 mA associated with a 0.12 W/A external efficiency is reported for as-cleaved device at room temperature. The maximum output power, the gain peak wavelength at threshold and the full width at half maximum of the spectral gain are 5 mW, 1512 nm and 60 nm, respectively. Although these performances must be improved in the future, these results constitute to our knowledge the state-of-the-art on InP(3 1 1)B substrate. These results are of great interest since QD-based lasers are expected to play a major role in the next generation telecommunication networks as low-cost devices.

1 Introduction

Low-cost, directly modulated lasers will play a major role in the next generation telecommunication links (local and metropolitan area network) for uncooled and isolator-free applications.

InP has been the reference material system for 1.55 μm applications. Actual laser sources are based on the InGaAsP/InP QW-active material. They exhibit typical threshold currents <10 mA and a characteristic temperature T_0 of ~60 K (20–80°C) [1, 2]. More recently, GaInAlAs/InP QW-based lasers showed an improved T_0 of ~90 K (20–120°C) owing to a higher conduction band offset. Lasers realised in this material system allowed data transmission over a 40 km fibre span at 10 Gbit/s up to 80°C [3, 4].

Temperature-insensitive lasers fabricated on GaAs are very attractive for low-cost, high-volume production owing to a reduced cost of GaAs wafers and a mature technology. Two approaches have been intensively investigated in the last decade, namely InAs quantum dots (QDs) and GaInAsN QW emitting in the 1.3 μm window.

GaInAsN(Sb) alloys grown on GaAs substrate further allow to extend the emission wavelength in the 1.55 μm band. This material system offers high electron confinement, a prerequisite for high T_0, and a high differential gain. A recent result of GaInAsNSb/GaAs QWs emitting at 1.55 μm shows a relatively low-threshold current density of 579 A/cm^2 with propagation losses of ~4.8 cm^{-1} [5]. However, because of a lower material gain, typical threshold currents of ridge waveguide lasers amount to 60 mA [6]. The less mature material development obviously needs further improvements.

QD-based lasers have attracted a lot of interest in the last decade owing to their expected remarkable properties arising from charge carrier confinement in three dimensions [7]. Low-threshold current densities [8], high material gain [8, 9], temperature insensitivity [10] and near-zero linewidth enhancement factor at the lasing wavelength [11, 12] have been reported. This latter property combined with a high damping factor [13] is of utmost importance because it should increase the tolerance to optical feedback in these devices and may also offer potential advantages for direct modulation without transmission dispersion penalty.

Many efforts have been devoted to the GaAs-based QD material system for emission in the 1.3 μm band, owing to a better material maturity [8–12], which allowed the demonstration of temperature-insensitive 10 Gbit/s transmission up to 85°C [14, 15]. However, for long-haul applications, lasers emitting at 1.55 μm emission is mandatory. Two different approaches can match this application: metamorphic QDs grown on GaAs and QDs grown on InP substrates.

Lasers emission up to 1.45 μm has recently been demonstrated using metamorphic InAs/GaAs QD layer. Typical threshold current density equals ~1–1.5 kA/cm^2, and characteristic temperature is of ~65 K (20–85°C) [16]. More recently, QD-coupled QW tunnel injection lasers has presented a very low threshold current density of 63 A/cm^2 and an interesting −3 dB modulation bandwidth of ~8 GHz [17]. But further extension of the emission wavelength at 1.55 μm on GaAs remains an issue.

So far, only QD-based active layers grown on InP allowed emission in the telecommunication window. Growth of QDs on (1 0 0) substrates has already been demonstrated using molecular beam epitaxy (MBE) [18] or molecular organic vapour-phase epitaxy [19]. Elongated dots, or so-called quantum dashes, have also

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been obtained by MBE [20, 21], which have led to the demonstration of high-performance lasers [22]. An alternative approach is the use of the InP(3 1 1)B orientation, which has also allowed to demonstrate 3D-confined nanostructures with a QD density as high as 10^{11} cm^{-2} [23] as well as low chirp of a 2.5 Gbit/s directly modulated single-mode waveguide laser emitting at 1.6 μm [24].

This article reports for the first time the realisation of an InAs/InP(3 1 1)B narrow-ridge single-mode laser emitting on the ground state at 1516 nm under continuous wave operation at room temperature. This is the first demonstration of lasing within the C-band (1525–1565 nm) for this material system.

2 Broad-area lasers

The laser heterostructure was grown by MBE on a (3 1 1)B InP substrate. The active region consists of five layers of self-assembled QDs grown through the Stranski–Krastinow mode. The QD layers are separated by 30 nm InGaAsP quaternary ($\lambda_g = 1.18$ μm) barriers (named Q1.18) located at the centre of a Q1.18 optical waveguide. The optical confinement layer corresponds to a laser cavity thickness of 435 nm. The growth process has been optimised by using the double-cap procedure as well as by controlling the arsenic flux. Regarding the double-cap procedure, already published in reference [25], it is used to reduce the size dispersion of the QDs. The double-cap procedure consists in growing the capping layer of the QDs already formed in two steps. The first capping layer, with a fixed thickness, is used to control the QD height. This layer is followed by a growth interruption under element V flux, which planarises the surface thanks to As/P exchange. The second capping layer is then added to complete the optical confinement layer. The maximum height of the QDs is therefore controlled by the height of the first capping layer, thus allowing a reduction of the QD size dispersion. As a result, the emission energy of the laser being linked to the QD size, the emitting wavelength can be controlled and tuned towards the aimed 1.5 μm telecommunication wavelength.

On the other hand, a reduction of the arsenic flux during the growth has been used to increase the QD density up to 10^{11} cm^{-2}. Indeed, it has been demonstrated in reference [26] that low arsenic pressure growth allows to achieve high density of QDs, with sizes comparable with QDs formed on GaAs substrates and presenting reduced size dispersion.

Such a QD density is of first importance to ensure an efficient lateral coupling between the dots, which has been shown to improve the laser efficiency for a well-selected coupling regime [27].

Fig. 1 is a 1 μm^2 atomic force microscopy image of uncapped dots grown as described earlier. This structural analysis has allowed determining QD dimensions. Diameter and height of 25 and 5 nm, respectively, have been deduced, as well as a QD density above 10^{11} cm^{-2}. However, the height of the first capping layer being set to 3 nm, the final height of covered dots is estimated to a maximum of 3 nm, as confirmed by TEM measurements [25]. The carrier confinement was then studied by magneto-photoluminescence (PL) in the QDs, depending on the composition of the first capping layer [28]. It was demonstrated that using Q1.18 provided better carrier confinement than InP by preventing intermixing effect observed in InAs/InP and InAs/GaAs QDs [29]. Cross-sectional scanning tunnelling microscopy measurements have confirmed the homogeneity of the InAs QDs [30].

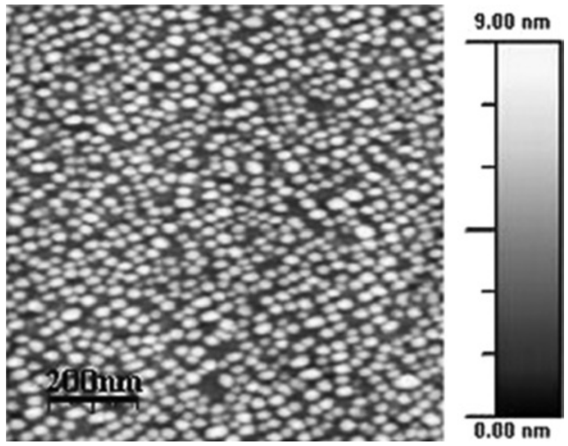

Fig. 1 *Atomic force microscopic view of a dot layer*

PL measurements were performed on this laser structure at room temperature under continuous laser excitation at 647 nm. In Fig. 2, the PL response is depicted: as it can be seen, the PL peak is centred at 1.51 μm, with a full width at half maximum (FWHM) of 58 meV corresponding to ~100 nm. This linewidth, which is comparable with the best values reported [31] on InP substrate, reveals a relatively low-size dispersion of the QDs. Room temperature GS lasing is observed under pulsed excitation for as-cleaved broad-area lasers of 50 μm width and cavity lengths ranging from ~800 to 1800 μm. For instance, a differential efficiency of 0.12 W/A per facet is demonstrated for a 1300 μm cavity length. In Fig. 3, the threshold current density is reported as a function of the inverse of cavity length. The threshold current density at an infinite cavity length often defined as the transparency current density is 400 A/cm^2. Consequently, the current density per QD layer is 80 A/cm^2. The Γg_0 modal gain can be derived from the slope of Fig. 3 [32] and amounts to ~16 cm^{-1}, that is, ~3.2 cm^{-1} per layer, which is close to typical results obtained on InAs/GaAs QD [33]. Fig. 4 shows the inverse external efficiency as a function of the cavity length and allows to estimate the internal loss at 10 cm^{-1}, which is a typical value on InP substrates.

3 Single-mode lasers

Single-mode ridge waveguide was etched by reactive ion etching using a $CH_4/H_2/O_2$:O_2 cyclical process optimised to obtain (anisotropic) vertical etching of the (3 1 1)B structure, with a SiNx etching mask. The O_2 passivating step was

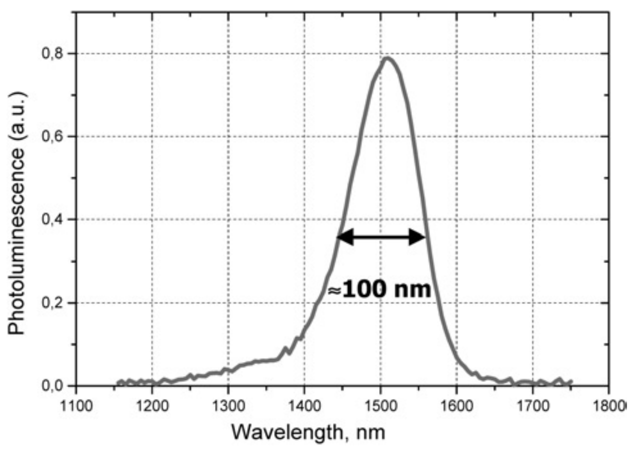

Fig. 2 *PL spectrum at room temperature, FWHM = 58 meV*

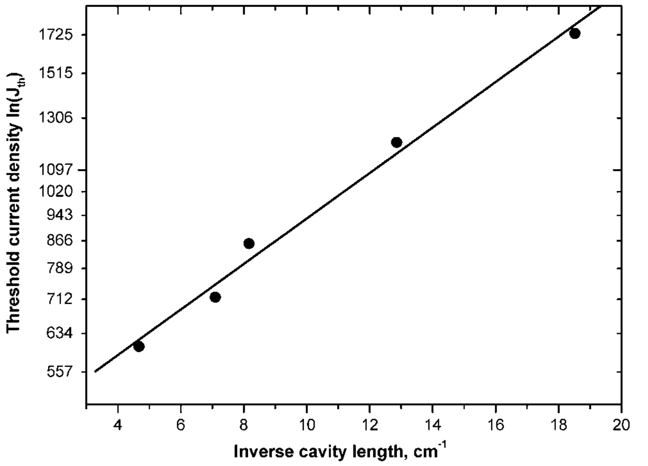

Fig. 3 LnJ_{th} *(log scale) versus 1/L for InAs/InP broad-area lasers of 50 μm width and cavity lengths ranging from ~800 to 1800 μm*

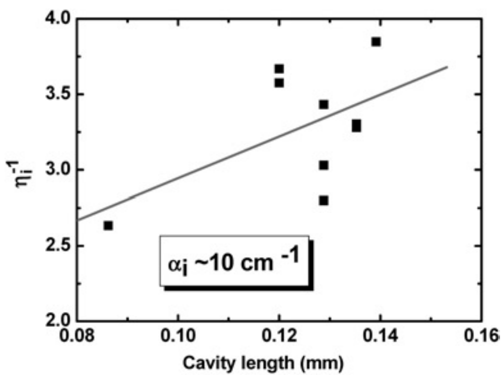

Fig. 4 *Inverse external efficiency as a function of cavity length*

optimised to obtain highly vertical ridge sidewalls with no lateral etching. A small amount of O_2 was also added in the etching step to compensate for a-C:H redeposition on all inert surfaces, including the mask inherent to the CH_4/H_2 mixture.

In Fig. 5*a*, an SEM view of the ridge on InP(3 1 1)B after the RIE etching is depicted: the ridge waveguide width is 2.5 μm. Fig. 5*b* shows the view of the ridge at the end of the process, where planarisation of the electrodes has been ensured by standard bisbenzocyclobutene processing.

Fig. 6 shows the light–current characteristics of an as-cleaved device of 1490 μm long cavity. The threshold current is equal to 60 mA under pulsed operation, whereas

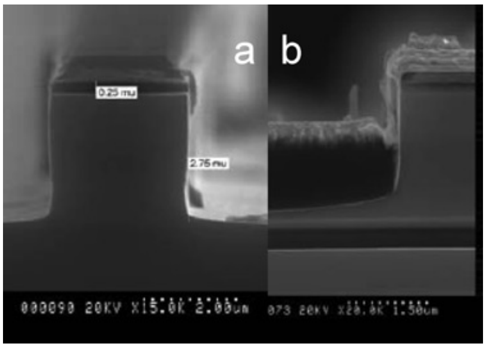

Fig. 5 *SEM view of a ridge on InP(3 1 1)B*

a After RIE etch
b At the end of process

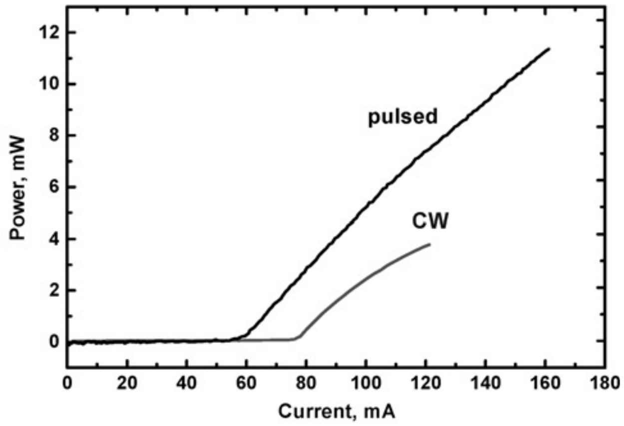

Fig. 6 *Light–current characteristic of a 1490 μm × 2.5 μm ridge laser measured under pulsed and CW operations at room temperature*

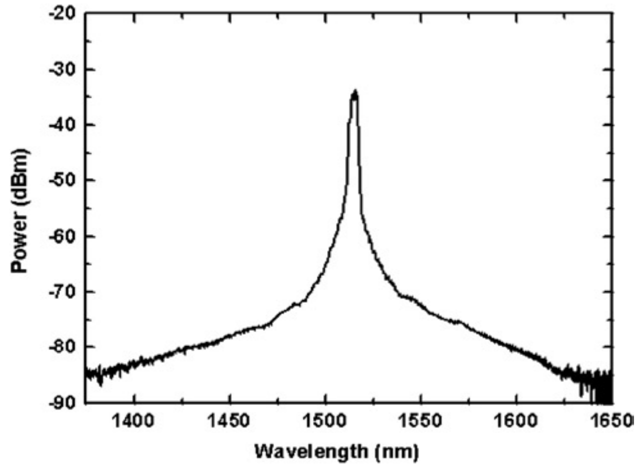

Fig. 7 *CW room temperature optical spectrum of a 1490 μm × 2.5 μm ridge laser measured (I = 1.85 I_{th} ≃ 111 mA)*

it goes up to 80 mA under CW operation because of heating effects. The maximum output power and external efficiency are, respectively, 11 mW and 0.12 W/A per facet under pulsed excitation (4 mW and 0.11 W/A, respectively, per facet under CW operation). Fig. 7 shows the optical spectrum recorded at $I = 1.85I$th (~111 mA). Transverse single-mode behaviour is demonstrated with a lasing wavelength of 1.51 μm. The net gain has also been investigated using the Hakki–Paoli method in the CW regime. In Fig. 8, the net gain ($\Gamma g - \alpha_i$) is reported as a function of injected current below threshold, using a

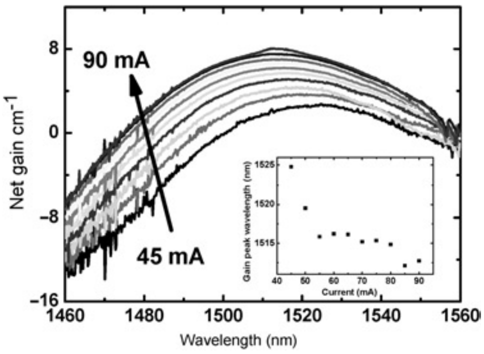

Fig. 8 *Net gain spectra in CW regime for current increasing from 45 to 80 mA (L = 1490 μm, threshold current equals 80 mA)*

high-resolution optical spectrum analyser (10 pm). Gain peak wavelength stays on ground state and shifts from 1526 to 1512 nm at threshold (inset in Fig. 8). The maximum FWHM of the spectral gain is close to 60 nm.

4 Conclusions

As a conclusion, a transverse single-mode InAs QD laser grown on InP (3 1 1)B substrate has been realised. The device, which contains five layers of QD, emits at 1516 nm close to the C-band of the telecommunications. It operates at room temperature and under continuous waves with a threshold current of 80 mA. The maximum output power remains limited since it does not exceed 5 mW while the external efficiency is 0.12 W/A. Although these performances must be improved, these results constitute, to our knowledge, the state-of-the-art on InP(3 1 1)B substrate. They also open the way to a further improvement, of QD laser performances at 1.55 μm on InP substrate, as already demonstrated for InAs–GaAs QDs at 1.3 μm.

5 Acknowledgment

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