Lasing of wavelength-tunable (1.55 μ m region) InAs/InGaAsP/InP (100) quantum dots grown by metal organic vapor-phase epitaxy

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Lasing of wavelength-tunable (1.55 μm region) InAs/InGaAsP/InP (100) quantum dots grown by metal organic vapor-phase epitaxy

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The authors report lasing of InAs/InGaAsP/InP (100) quantum dots (QDs) wavelength tuned into the 1.55 μm telecom region. Wavelength control of the InAs QDs in an InGaAsP/InP waveguide is based on the suppression of As/P exchange through ultrathin GaAs interlayers. The narrow ridge-waveguide QD lasers operate in continuous wave mode at room temperature on the QD ground state transition. The low threshold current density of 580 A/cm² and low transparency current density of 6 A/cm² per QD layer, measured in pulsed mode, are accompanied by low loss and high gain with an 80-nm-wide gain spectrum. © 2006 American Institute of Physics.

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Owing to their atomic-like energy states, semiconductor quantum dots (QDs) enable superior performance of optical devices such as lasers and semiconductor optical amplifiers (SOAs) and are potential candidates for future solid-state quantum information and communication.^{1–3} Their compatibility with fiber-based optical telecommunication systems demands device operation in the 1.55 μm wavelength region. Up to now, QDs are most widely studied in the GaAs-based materials system, and InAs/GaAs QD lasers have been realized in the 1.3 μm wavelength region^{4,5} and close to 1.55 μm with metamorphic QDs,⁶ which was also achieved by dilute-N GaInNAs and GaInNAsSb quantum wells (QWs).^{7,8} On the other hand, the InP-based materials system easily covers the full range of optical-networking wavelengths dominant for photonic devices in the 1.55 μm wavelength region employing bulk and QW active regions. Moreover, it is ideally suited for monolithic photonic integration, supporting all key optical functions, including lasers, SOAs, phase modulators, detectors, and passive waveguides on a single chip.^{9,10} Unfortunately, however, the emission of InAs/InP QDs is usually beyond 1.6 μm at room temperature (RT) due to As/P exchange during InAs growth resulting in too big QDs,¹¹ especially when grown by metal organic vapor-phase epitaxy (MOVPE) to comply with production standards.

Here we report lasing of wavelength-tunable InAs/InGaAsP/InP (100) QDs in the 1.55 μm region grown by MOVPE. Wavelength control of the QDs is achieved through insertion of ultrathin GaAs interlayers underneath the InAs QDs. The GaAs interlayer reproducibly suppresses As/P exchange to continuously reduce the QD height and emission wavelength as a function of thickness, providing an independent parameter for high flexibility.¹² The narrow ridge-waveguide QD lasers operate in continuous wave (cw) mode at RT on the QD ground state transition. The low threshold current density of 580 A/cm² and low transparency current density of 6 A/cm² per QD layer measured in

pulsed mode are accompanied by low loss and high gain with an 80-nm-wide gain spectrum.

The QD laser is grown by MOVPE on *n*-type InP (100) substrates. Fivefold stacked InAs QD layers (3.5 ML InAs, 1 ML GaAs interlayer, and 40 nm InGaAsP separation layers¹³) are placed in the center of a 500 nm thick lattice-matched InGaAsP waveguide core with a band gap at $\lambda_Q = 1.25 \mu\text{m}$ (Q1.25 InGaAsP). The width, height, and area density of the QDs are 30–60 nm, 4–7 nm, and $\sim 3 \times 10^{10} \text{ cm}^{-2}$, and the photoluminescence (PL) peak wavelength and linewidth are 1.58 μm and 110 meV, respectively. Bottom and top claddings of the laser structure are 500 nm *n*-InP buffer and 1.5 μm *p*-InP completed by a compositionally graded 75 nm *p*-InGaAsP contact layer. The width of the ridge waveguide w_{ridge} is 3.5 μm , and the cavity length is between 1 and 3.6 mm. A cross-sectional scanning electron microscopy image of the ridge-waveguide laser, planarized by polyimide is shown in Fig. 1.

Being compatible with photonic integration, the Q1.25 InGaAsP waveguide core compromises maximum confinement energy of the QDs (small λ_Q) for temperature stability of active devices with a large electro-optic effect (large λ_Q) for phase modulation. Moreover, a large refractive index contrast with respect to the waveguide cladding is maintained for large λ_Q , implying strong vertical optical mode confinement for compact devices. InAs/InP QD lasers re-

FIG. 1. (Color online) Cross-sectional SEM image of the QD laser structure.

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FIG. 2. (Color online) (a) EL and lasing spectra taken at RT of the narrow ridge-waveguide QD lasers with cavity length L of 1 and 3.6 mm in cw mode. (b) EL and lasing spectra taken at RT in pulsed mode of the 1-mm-long device for different currents. The resolution of the optical spectrum analyzer is 0.5 nm.

ported so far have employed larger band gap waveguide cores or even Al-containing material,^{14–16} which is not preferred due to severe surface contamination and polycrystalline deposition on dielectric masked areas hindering defect-free selective active-passive regrowth.

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. 2(a). Measurements are performed at RT in cw mode. The light is coupled out through a lensed fiber and led to either an optical spectrum analyzer or power meter. For the 1-mm-long device, lasing wavelength and threshold current (I_{th}) are 1.57 μm and 125 mA, respectively, corresponding to a threshold current density (J_{th}) of 3.6 kA/cm². J_{th} is reduced to 1 kA/cm² for 3.6 mm device length owing to lower relative mirror loss, and the lasing wavelength is increased to 1.65 μm. Lasing occurs on the QD ground state transition. This is proven by the appearance of simultaneous ground state lasing (at 1.57 μm at threshold) and excited state lasing (at 1.54 μm) at larger currents shown in Fig. 2(b) for the 1-mm-long device. We observe simultaneous ground and excited state lasing, reported previously,^{17–19} only for pulsed current injection (165 ns pulse width and 300 kHz repetition rate) with

FIG. 3. (Color online) Basic laser characteristics measured at RT in pulsed mode. (a) Linear dependence of the threshold current density (open circles) and lasing wavelength (closed circles) as a function of the reciprocal cavity length. (b) Reciprocal total external differential quantum efficiency $1/\eta_{ext}$ vs laser cavity length. Inset: Light output power vs injection current curves from lasers with different cavity lengths L .

the ground state lasing wavelength unaffected. This indicates that the relatively slow phonon-assisted carrier relaxation, necessary for simultaneous population inversion of ground and excited states under pulsed conditions, is overcompensated by carrier-carrier scattering in cw mode. Devices shorter than 1 mm only lase on the excited state due to ground state gain saturation with drastically increased J_{th} .

For evaluation of the basic laser parameters measurements are performed in pulsed mode to avoid uncontrolled heating. Figure 3(a) shows J_{th} and the lasing wavelength, measured at $1.15I_{th}$, as functions of the reciprocal cavity length. The redshift of the lasing wavelength with increasing cavity length is related to the QD size distribution. For long devices, lower density and larger QDs with emission at the long wavelength side of the PL spectrum already support lasing. For shorter devices, higher density and smaller QDs with shorter emission wavelengths toward the PL peak are required.²⁰ For long devices, this is likely facilitated by thermally activated redistribution of carriers preferentially from smaller to larger QDs.

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/cm² for the 3.6-mm-long device. Extrapolation of the linear dependence of J_{th} on the inverse cavity length to zero yields the transparency current density of 30 A/cm², i.e., 6 A/cm² per QD layer. The characteristic

FIG. 4. (Color online) Net modal gain vs wavelength for different currents (open circles) determined from the subthreshold ASE spectra taken at RT in cw mode of the 1-mm-long device. The solid lines show parabolic fits and the horizontal arrow indicates 3 dB amplification.

temperature (T_0) determined from the temperature dependence of J_{th} of several devices is 35–50 K between 10 and 20 °C, and 25 K between 20 and 30 °C. These relatively low T_0 values are governed by thermionic emission of carriers from the QDs to the barriers^{15–17} and can be improved by device design such as the dot-in-well structure²¹ or by enabling tunnel injection.⁴ The temperature dependence of the QD lasing wavelength reveals a small temperature coefficient, independent of device length, of +0.12 nm/K (redshift) between 10 and 20 °C, comparable to that induced by the refractive index change. From 20 to 30 °C the temperature coefficients are –0.5 and –0.65 nm/K (blueshift) for long and short devices, indicating increasing losses due to carrier escape, compensated by the larger gain of higher density (shorter wavelength) QDs.

Figure 3(b) shows the reciprocal total external differential quantum efficiency ($1/\eta_{ext}$) deduced from the light output power versus current curves in the inset, as a function of the cavity length. A linear behavior is observed in the regime of ground state lasing. The internal optical loss (α_i) and the internal differential quantum efficiency (η_i) are deduced from the linear fit according to $1/\eta_{ext} = (1/\eta_i)[1 + \alpha_i L / \ln(1/R)]$ to be 4.2 cm^{–1} and 37%, respectively. The maximum QD ground state modal gain is 14.7 cm^{–1} at 1.57 μm, determined 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. Together with the low transparency current density of 6 A/cm² per QD layer, the above values are among the best achieved,^{14–16} indicating the excellent quality and performance of our QDs despite the lower confinement energy and QD density.

The gain spectrum, important for broadband SOAs and widely tunable lasers, is determined by fitting the Fabry-Pérot resonances in the cw amplified spontaneous emission (ASE) spectra below threshold.²² The net modal gain, which includes the internal loss, as a function of wavelength is shown in Fig. 4 for the 1-mm-long device at different currents. The gain peak wavelength blueshifts with increasing current, revealing enhanced filling of smaller QDs. The

maximum achievable QD ground state net modal gain is 10 cm^{–1} at 3.5 kA/cm² current density, again taking into account that shorter devices only lase on the excited state. The maximum differential gain per current is 0.075 cm^{–1}/mA. The bandwidth of the gain spectrum at 3 dB amplification, the hallmark for SOA operation, is 80 nm for this 1-mm-long device.

In summary, lasing is achieved for MOVPE-grown InAs/InGaAsP/InP (100) QDs wavelength tuned into the 1.55 μm region through insertion of ultrathin GaAs interlayers for applications in fiber-based optical telecommunication systems. The narrow ridge-waveguide lasers with five-fold stacked InAs QD active layers operate in cw mode at RT on the QD ground state transition. The low J_{th} of 580 A/cm² and low transparency current density of 6 A/cm² per QD layer, measured under pulsed conditions, are accompanied by low internal loss of 4.2 cm^{–1}, high internal differential quantum efficiency of 37%, high maximum QD ground state modal gain of 15 cm^{–1}, and an 80-nm-wide 3 dB gain spectrum.

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