InAs/InP Quantum Dot Fabry-Pérot and Ring Lasers in the 1.55 µm Range using Deeply Etched Ridge Waveguides

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In this paper we report on the fabrication and characterization of InAs/InP (100) quantum dot Fabry-Pérot and ring lasers, lasing in the 1.55 µm wavelength range and employing narrow deeply etched ridge waveguides (1.65 µm width). Sidewall recombination effects at the deeply etched waveguides appear not to affect the performance of the lasers. Narrow deeply etched ridge waveguides can be mono-mode and allow for a small bending radius to realize compact integrated devices. As a demonstration we present results on a compact ring laser.

Introduction

Quantum dot (QD) lasers and amplifiers are of great interest for optical telecommunication. QD lasers have a very low transparency current density per dot layer, a wide gain bandwidth and can have a much lower threshold current density [1] compared to bulk or quantum well lasers. For the use of QD lasers and amplifiers in optical integrated circuits for telecommunication, there are two important aspects. The first is the operation in the C and L band; the second is the option to have deeply etched mono-mode ridge QD waveguide amplifiers which allow for significantly more compact devices. QD material has the advantage over other active materials with respect to the spreading and sidewall recombination [2] of injected carriers. It has been reported in [3] that PL intensities of 1.2 µm InAs QDs deeply etched mesas depend weakly on the mesa size down to 200 nm. Deeply etched InAs/GaAs QD lasers have been reported with waveguide mesa widths down to 1 µm in the 1.3 µm wavelength range [4]. A ring laser at 1.3 µm has also been reported [5], with a 10.28 mm long ring shallowly etched. In this paper we present first results on InAs/InP (100) QD lasers, lasing in the 1.55 µm wavelength range, with mono-mode deeply etched waveguides (1.65 µm width). The presented lasers are Fabry-Pérot (FP) and ring cavity types. All our high contrast deeply etched QD lasers have the same threshold current density as shallowly etched ones and do not deteriorate over many hours of operation. It appeared that due to the low absorption of the QDs, the output waveguides of the ring lasers do not need to be contacted and injected with current for operation with reasonable output power. This shows that for specific applications QD active materials offer the possibility to integrate active and passive devices on a single chip in a uniform layer stack.

Fabrication process

The QD laser structure was grown on n-type InP (100) substrates by metal organic vapor-phase epitaxy (MOVPE). In the active region, five-fold stacked InAs QD layers separated by 40 nm thick InGaAsP (Q = 1.25 µm; Q1.25) were placed in the center of a

500 nm thick lattice-matched Q1.25 waveguide core. The choice of the Q1.25 waveguide core is the result of an optimization made with regards to the application of this material in active/passive photonic integration using selective area regrowth [6]. It is a compromise between the maximum confinement energy of the QDs for temperature stability of active devices, a large electro-optic effect for phase modulators in passive areas, and maintaining a large refractive index contrast for strong vertical optical mode confinement. The nominal InAs amount for QD formation was 3.5 monolayers (MLs). One ML GaAs interlayer was inserted underneath each QD layer to suppress unwanted As/P exchange reactions during QD growth to tune the QD emission wavelength into the 1.55 µm region [7]. 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 device performance of shallowly etched narrow ridge waveguide QD lasers processed from the same material is reported in [8]. The waveguides have been processed using Reactive Ion Etching (RIE). For electrical isolation between contacted waveguides, the contact layer and part of the top cladding were removed. Before contacting, the waveguides have been planarized by polyimide.

Fabry-Pérot laser results

The cavity length of the 1.65 µm wide deeply etched FP QD laser is 2.0 mm, defined by cleaving. The cleaved facets are un-coated. Comparison with the shallowly etched QD lasers shows that lasing occurs on the QD ground states [8]. The threshold current density in continuous wave (CW) operation is 3.3 kA/cm² at 15°C, which is the average value for eight different lasers. Most remarkable, the threshold current density is the same as that of the 2 µm wide shallowly etched ridge QD lasers which are on the same chip. This demonstrates that the performance of the deeply etched lasers does not suffer from surface recombination at the etched sidewalls due to the three-dimensional confinement of injected carriers in the QDs [2]. The QD lasers did not degrade with time as compared with bulk lasers fabricated in the same way, where lasing stops after one hour when pumped at twice the initial threshold current.

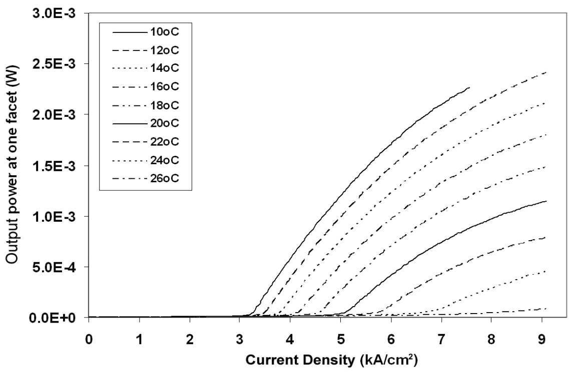

Figure 1: Output power at one facet of the deeply etched FP QD laser as a function of current density for different temperatures. The light was collected using an objective lens (NA = 0.65).

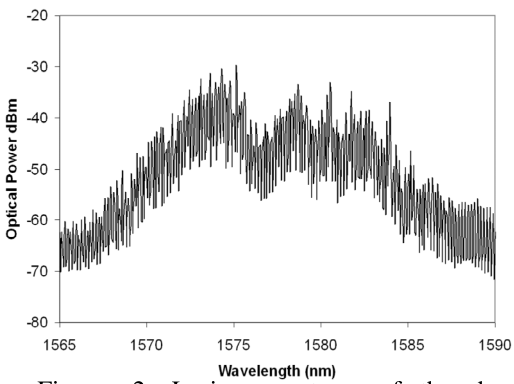

Figure. 2. Lasing spectrum of the deeply etched FP QD laser for I = 300 mA and T = 12°C, (resolution 0.1 nm).

The optical output power of the FP QD laser from one facet as a function of the current density for different temperatures in CW operation is plotted in figure 1. The light was collected using an objective lens (NA = 0.65). Output powers up to a few milliwatts are obtained. From the PI curves a value of the characteristic temperature T_0 of 20 K at room temperature is determined, the same value as that for shallowly etched lasers. This relatively low T_0, for CW operation, is dominated by thermionic emission of carriers from the QDs to the Q1.25 barriers. Figure 2 shows a typical lasing spectrum. The wide lasing spectrum is due to the 80 nm gain bandwidth [8] and the inhomogeneous character of the QD gain medium. For the eight lasers measured, the central wavelength varies from 1565 nm to 1595 nm.

Ring laser results

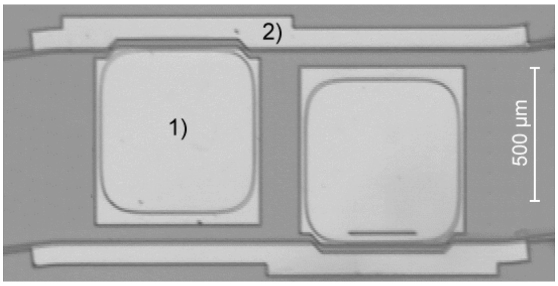

Figure 3: Top view of two QD ring lasers with two separate electrical contacts, 1) for the ring and the directional couplers and 2) for the output waveguides.

A photograph of two realized compact QD ring lasers is presented in figure 3. The deeply etched waveguides are visible as dark lines. The rings are 2.0 mm long. The bends have a radius of curvature which decreases adiabatically down to 100 µm in order to avoid offsets between straight and curved waveguides which can give rise to reflections. The directional coupler is double-etched with the gap shallowly etched and the outer ridges deeply etched to increase the fabrication tolerances [9]. The coupler is 200 µm long and the gaps vary from 0.9 to 1.2 µm in width resulting in output coupling efficiency between 25 and 50 %. The reflectivity of the cleaved facets of the output waveguides is reduced by the 7° angle and anti-reflection coating. The lasers have two separate electrical contacts, one for the rings and the directional couplers and another one for the two output waveguides.

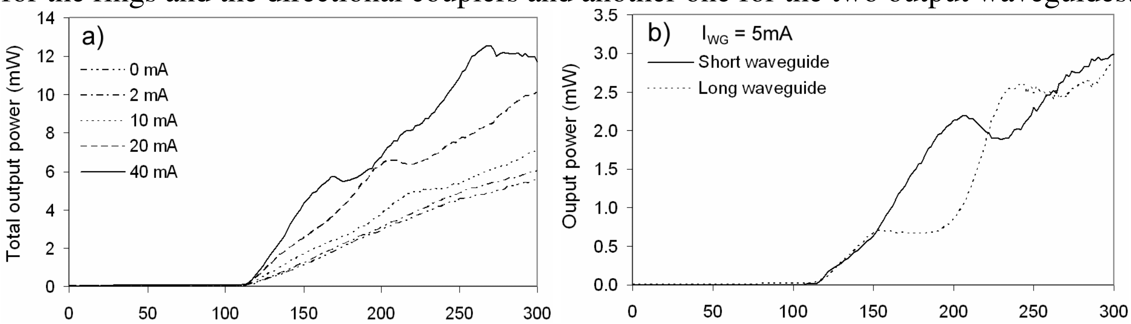

Figure. 4: a) Total optical output power as a function of I_{Ring} for different I_{WG}. b) Short and long output waveguides power as a function of I_{Ring} for I_{WG} = 5mA. The output powers are corrected for coupling and optical isolator losses. T = 12°C. The directional coupler gap is 1.2 µm.

In figure 4 a), the total optical output power from the long and short output waveguides of the QD ring laser with a directional coupler gap of 1.2 µm is plotted as a function of ring current (I_{Ring}), for different current values in the output waveguides (I_{WG}). Operation is in CW mode at 12°C. The output powers are corrected for lensed fiber coupling and optical isolator losses. The total current for transparency of the QD gain material in the output waveguide is estimated at 3 mA [8]. The low absorption of the QDs allows for use of the ring laser without pumping the output waveguides. In unpumped FP lasers, an optical loss of 10 dB/cm ± 1dB around 1555 nm has been measured by injecting 1 mW from an EDFA broadband source. The presented light versus current (LI) curves are not linear above 10 mA pump current in the output waveguides due to the spontaneous emission generated there injected into the ring. In figure 4 b) output powers are plotted from the two outputs separately as a function of I_{Ring} for I_{WG} = 5 mA. The laser is operating bi-directional; however, above 150 mA some power is transferred between the clockwise and counter clockwise modes. The lasing spectra of the ring laser are similar to those of the FP lasers, but with a 40 GHz FSR.

Conclusion

We have presented the results on InAs/InP QD Fabry Pérot and ring lasers using narrow deeply etched waveguides (1.65 µm width) and lasing in the 1.55 µm wavelength range. We have observed that the performance of such lasers does not suffer noticeably from surface recombination of injected carriers. The deeply etched lasers have the same threshold current densities as shallowly etched ones and do not deteriorate with time. These observations show that more compact integrated photonic devices can be realized through the use of deeply etched bends with a small radius of curvature. This was demonstrated by the realization of small ring lasers. The measurements performed with unpumped output waveguides of the ring lasers, due to the low absorption and transparency current densities, reveal that QD gain materials offer further increased flexibility for photonic integration for specific applications. Short sections of unpumped waveguides are easily bleached with limited power loss. One can consider to integrate lasers, photodetectors and passive waveguides for interconnection, using the same layer stack and thus avoiding sophisticated active-passive integration technology.

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