Wide emission spectrum from superluminescent diodes with chirped quantum dot multilayers

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L.H. Li, M. Rossetti, A. Fiore, L. Occhi and C. Velez

A superluminescent diode (SLED) using chirped multiple InAs quantum dot (QD) layers as the active region is demonstrated. The fabricated QD SLEDs exhibit a large spectral width up to 121 nm, covering the range 1165–1286 nm.

Introduction: Superluminescent diodes (SLEDs) are the light sources of choice in optical measurement systems needing a broad emission spectrum, such as gyroscopes, fibre-optics sensors and optical coherence tomography. Large spectral width is one of the most important features of SLEDs [1, 2], as the correspondingly short coherence length can significantly improve the spatial resolution in coherence-based systems. Multiple quantum wells engineering is a flexible approach that has been extensively used to broaden the spectral width of SLEDs [3]. Recently, it was proposed that the naturally-occurring size dispersion in self-assembled growth of quantum dots (QDs) can be beneficial to SLEDs requiring larger spectral width [4]. SLEDs using stacked In(Ga)As/GaAs QD layers emitting around 1000 nm have been demonstrated [5, 6] with a spectral width of 80 nm. To further increase the spectral width of QD SLEDs, a deliberate increase of the dot size distribution has been suggested [4]. However, the exact control of the QD size dispersion is not easily reproducible. Another possible approach would be to use chirped multiple QD layers with different amounts of InAs deposition in the QDs, as proposed in [5, 6]. Since the amount of InAs also affects the density and radiative efficiency of the QDs, this last approach is difficult to implement, too.

In contrast, in this Letter we propose the control of the emission wavelength in the chirped structure by a change in the matrix surrounding the QDs. Specifically, when the QDs are covered by an InGaAs strain-reducing layer (SRL), a red-shift of the emission wavelength is observed, depending on the composition and thickness of the SRL [7, 8]. The areal density is not significantly affected by the capping, so that the available gain and the wavelength are effectively decoupled. We demonstrate that using stacking chirped multiple InAs QD layers with different InGaAs SRL (varying either In composition or thickness of InGaAs layer), a spectral width of 78 nm can be obtained in the photoluminescence (PL) spectrum of the QD ground state (GS). By combining the emission from GS and excited state (ES) of QDs, a spectral width of 121 nm, covering from 1165 to 1286 nm, was achieved in a QD SLED. In contrast to other approaches, this technique is reproducible and easy to implement, since it relies on well-controlled growth parameters.

Experimental setup: The device growth was performed using solid-source molecular beam epitaxy on n^+-GaAs substrate. QDs were formed by continuous deposition of InAs material at the growth temperature of 530°C and growth rate of 0.163 μm/h. The active region consists of five stacks of InAs QDs separated by a 40 nm GaAs barrier. Each layer of InAs QDs is capped by a 5 nm $In_xGa_{1-x}As$ SRL. The In composition in the different layers is varied from 0.09 to 0.15 by an interval of 0.015. The active layers were grown at the centre of a 310 nm-thick GaAs undoped waveguide. Next to the GaAs waveguide, graded index-separating confinement heterostructures (GRINSCH) were grown. The n- and p-type cladding layers consist of 1.5 μm-thick $Al_{0.8}Ga_{0.2}As$ material. 1 μm-thick cladding layers far from the active region were doped with Si and Be to 1×10^{18} cm^{-3}, respectively. The doping level in approximately 0.5 μm-thick cladding layers close to active region was intentionally reduced to 2×10^{17} cm^{-3} in order to reduce the optical loss induced by free-carrier absorption. The structure was capped with a 40 nm p^+-GaAs contact layer ($p = 2 \times 10^{19}$ cm^{-3}). Fabrication starts with the reactive-ion etching of 8 μm-wide ridges, stopping at ~300 nm above the GRINSCH layer. The ridge was orthogonal to the cleaved facets for test laser structures and tilted by 7° in SLEDs to suppress lasing. After etching, the unetched areas were passivated by wet oxidation of the AlGaAs cladding layer, thus forming a self-aligned current aperture [9]. The fabrication was completed by substrate thinning and p- and n-contact metallisation.

Measurements: Room temperature (RT) PL measurement was performed on a reference chirped multiple InAs QDs structure grown in the same conditions as the device. A spectral width of 78 nm (full-width at half-maximum) was observed from the GS emission centred on 1270 nm, as shown in Fig. 1 (continuous line). A schematic drawing of the band diagram in chirped InAs QDs is shown in the inset. The achieved spectral width is much larger than the typical spectral width of 44 nm from the single-layer QD sample (Fig. 1, broken line). The high energy tail merging with the main peak comes from the first ES transition. To validate the device structure, we first processed a part of the as-grown wafer into 5 μm-wide ridge-waveguide edge-emitting lasers. Fig. 2 shows the measured emission spectra in pulsed operation from a 2 mm-long device at different injection currents. Well above GS lasing threshold of 180 A/cm^2, an extremely broad lasing spectrum of >30 nm is observed, which stems from the combined effect of the broad gain spectrum of the chirped QD active region and of the decoupling of the spatially-separated QDs. At a current density of 6000 A/cm^2, simultaneous lasing from both GS and ES is observed, owing to the relatively slow carrier relaxation rate and population saturation in the GS, as previously reported [10].

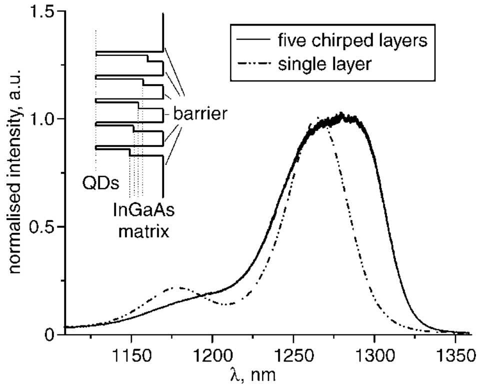

Fig. 1 *Normalised RT PL spectra of single-layer InAs QD sample and chirped multiple InAs QDs sample*

Inset: Schematic band diagram of chirped QD structure

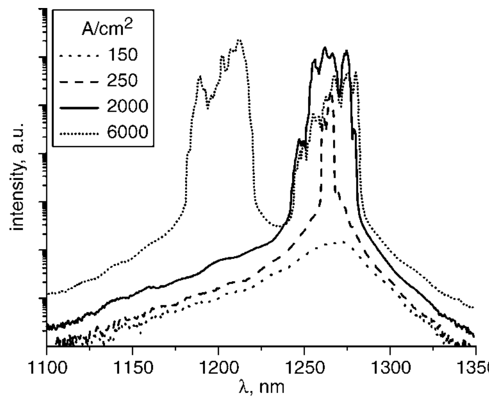

Fig. 2 *Emission spectra of 5 μm × 2 mm laser with chirped QD multilayer active region at different injection currents*

Uncoated QD SLEDs with tilted facets were tested in pulsed operation (1 μs pulses, 5% duty cycle). The emission spectra of a 4 mm-long device at various injection currents are presented in Fig. 3*a*. At low injection current, the emission from the GS dominates. With increasing injection current, GS saturates. The carriers begin to fill the ES, resulting in a broadening of spectrum on the short wavelength side (at current density of >1550 A/cm^2, the ES emission eventually dominates the spectrum, owing to the higher maximum gain on the ES). At current density of 940 A/cm^2, due to simultaneous contribution of the two states, a combined spectral width of 121 nm is obtained, with a 3 dB dip between the GS and ES peaks. By increasing the span of In composition in InGaAs SRL and thus further broadening the spectrum, the dip may be eliminated, leading to a flat and ultra-wide emission spectrum. The typical light–current curve under pulsed operation is shown in Fig. 3*b*. The maximum power of around 1.5 mW is limited by the density of states, and could be improved by increasing the QD areal density, the number of stacked layers or the device length, and by applying antireflective coatings.

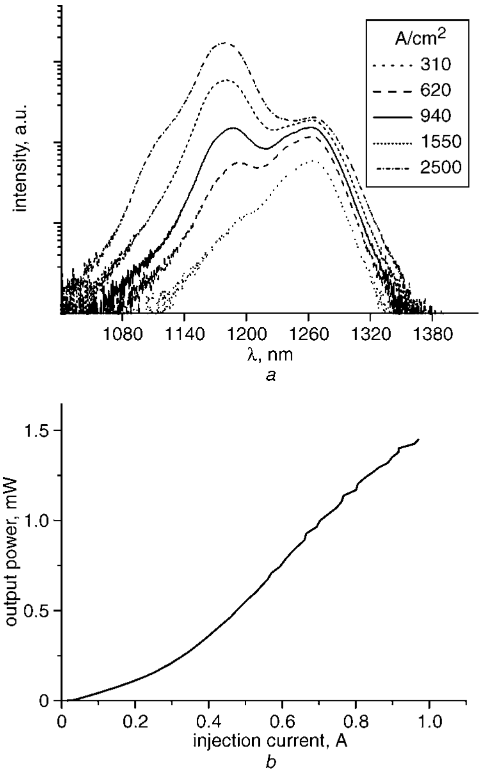

Fig. 3 *Emission spectra and typical light–current curve*

a Emission spectra of 8 μm × 4 mm QD SLED at various injection currents
b Typical light–current curve under pulsed operation

Conclusions: The technique of chirped QD multilayers is introduced as a means of reproducibly broadening the gain spectrum of a QD active region. QD SLEDs with chirped multiple InAs QD layers have been fabricated, showing a large spectral width of 121 nm. The same concept can be applied to other broad-gain devices such as semiconductor optical amplifiers and tunable lasers.

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References

1 Kondo, S., *et al.*: 'Very wide spectrum multiquantum well superluminescent diode at 1.5 μm', *Electron. Lett.*, 2000, **36**, (25), pp. 2093–2095
2 Burns, W., Chen, C.L., and Moeller, R.: 'Fiber-optic gyroscopes with broad-band sources', *J. Lightwave Technol.*, 1983, **1**, pp. 98–105
3 Lin, C.F., and Lee, B.L.: 'Extremely broadband AlGaAs/GaAs superluminescent diodes', *Appl. Phys. Lett.*, 1997, **71**, pp. 1598–1600
4 Sun, Z.Z., *et al.*: 'Quantum-dot superluminescent diode: a proposal for an ultra-wide output spectrum', *Opt. Quantum Electron.*, 1999, **31**, pp. 1235–1246
5 Heo, D.C., *et al.*: 'High power broadband InGaAs/GaAs quantum dot superluminescent diodes', *Electron. Lett.*, 2003, **39**, (11), pp. 863–865
6 Zhang, Z.Y., *et al.*: 'High performance quantum-dot superluminescent diodes', *IEEE Photonics Technol. Lett.*, 2004, **16**, (1), pp. 27–29
7 Chen, J.X., *et al.*: 'Tuning InAs/GaAs quantum dot properties under Stranski-Krastanov growth mode for 1.3 μm applications', *J. Appl. Phys.*, 2002, **91**, (10), pp. 6710–6716
8 Nishi, K., *et al.*: 'A narrow photoluminescence linewidth of 21 meV at 1.35 μm from strain-reduced InAs quantum dots covered by $In_{0.2}Ga_{0.8}As$ grown on GaAs substrates', *Appl. Phys. Lett.*, 1999, **74**, pp. 1111–1113
9 Markus, A., *et al.*: 'Impact of intraband relaxation on the performance of a quantum-dot laser', *IEEE J. Sel. Top. Quantum Electron.*, 2003, **9**, pp. 1308–1314
10 Markus, A., *et al.*: 'Simultaneous two-state lasing in quantum-dot lasers', *Appl. Phys. Lett.*, 2003, **82**, pp. 1818–1820