Flat-topped emission centred at 1 250 nm from quantum dot superluminescent diodes

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We present a method for tailoring a broadband and flat-topped emission spectrum in quantum dot superluminescent diodes based upon modification of the dots-in-compositionally-modulated-well (DCMWELL) technique. We demonstrate flat-topped emission with 95 nm full width at half maximum (FWHM), centred at 1 250 nm, and with output power in excess of 8 mW.

Key words: quantum dot, superluminescent diode, broadband

Introduction

Superluminescent light-emitting diodes (SLDs) provide broadband emission for a wide range of applications such as wavelength division multiplexed (WDM) system testing, fibre-optic gyroscopes and optical coherence tomography.[1] Recent interest has focused upon applications in optical coherence tomography, in which cheap, compact, high-power broadband optical sources are required in order to realise low cost point of care screening and diagnostics.[1] Operating wavelengths in the region of 1 050 nm to 1 250 nm are required as these correspond to attenuation minima in ocular media and skin tissue. Ultra-high resolution two- or three-dimensional cross-sectional images of tissue may be obtained non-invasively and *in situ.*[2]

Techniques to broaden the optical spectrum of semiconductor SLDs previously relied on emission wavelength shifted,[3] or intermixed,[4] quantum wells. Recently, quantum dot materials have attracted attention due to their naturally broad emission spectrum.[5] We previously demonstrated a technique for further broadening the emission bandwidth of a SLD operating at around 1 250 nm through modification of the dots-in-a-well (DWELL) design. A smooth increase in wavelength was observed as the indium (In) composition in a DWELL increased from 0% to 20%.[6] Our previous broadband SLD design relied upon a multi-DWELL structure, with each well containing a different indium composition chosen to fill the spectral range between lower and higher composition, with a Gaussian distribution. These structures were termed dots-in-compositionally-modulated-wells (DCMWELLs) and exhibited an almost Gaussian profile spectra with full width at half maximum (FWHM), typically about 85 nm. Passive components of the optical coherence tomography system can cut off the spectral edges of the signal, resulting in a non-Gaussian signal and the appearance of sidelobes in the interferometric autocorrelation. The signal should preferably be Gaussian in the frequency domain, hence a flat-topped spectrum would broaden the usable spectral range.

In this letter we demonstrate a novel scheme capable of broadening the spectrum to 95 nm whilst tailoring the profile of the emission to a flat-topped spectrum.

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Sample growth and fabrication

The quantum dot SLD structures were grown by molecular beam epitaxy on Si-doped GaAs (100) substrates. A schematic of the layer structure is shown in Fig. 1. The active regions were composed of five DWELL layers consisting of 3.0 monolayers of InAs grown upon 2 nm of $In_xGa_{1-x}As$ and covered by 6 nm of $In_xGa_{1-x}As$. The DWELLs were separated by 50 nm GaAs barriers and embedded between 150 nm separate confinement heterostructure GaAs layers. Two indium cells were utilised: one to deposit the low growth rate InAs quantum dots, and a second to deposit the faster InGaAs quantum well structure. The active region was sandwiched between 1 500 nm $Al_{0.4}Ga_{0.6}As$ cladding layers and a 300 nm GaAs contact layer completed the growth. Growth temperatures were 620°C for the AlGaAs and 510°C for the indium-containing layers. Following the deposition of each DWELL, the initial 15 nm of the GaAs spacer layer was deposited at 510°C, following which the temperature was increased to 580°C for the remaining 35 nm. The temperature was then reduced to 510°C for the growth of the next DWELL. The indium composition, x, of the $In_xGa_{1-x}As$ was optimised at 15% for the DWELL. For the 'standard' DCMWELL, as demonstrated by Ray *et al.*,[7] the five $In_xGa_{1-x}As$ wells contained x = 12%, 13%, 13.5%, 14% and 15%, respectively, with the gain spectrum resulting from the 13%, 13.5% and 14% DWELLs filling in the spectral range between the 12% and 15% DWELLs. This change in indium composition was achieved by changing the temperature of the cell while the barrier layers were grown.

For the flat-topped spectrum presented in this letter, a 3 × 2 arrangement was designed. If In_x compositions of the well are chosen such that the peak separation is equal to the linewidth (σ) for each DWELL's emission, then a flat-topped spectrum will occur. A 3 × 2 arrangement in which two DWELLs of three indium compositions (12%, 13.5%, 15%) was chosen such that the individual peaks were separated by their linewidth according to the schematic diagram in Fig. 2. For quantum dots with peak emissions from 1 250 nm to 1 300 nm, linewidth was found to be about 38 nm, hence the three different DWELL indium compositions were chosen to yield peak emissions separated by 38 nm. This was achieved by interpolating from a plot of peak

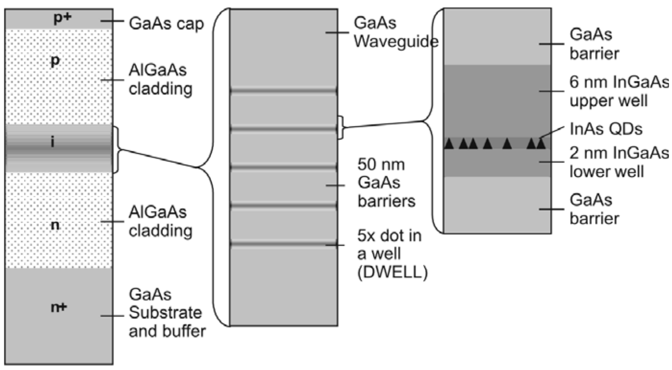

Fig. 1. Schematic of the device structure showing the pin diode (left) with an expanded view of the waveguide core (centre) and the quantum dot active region (right).

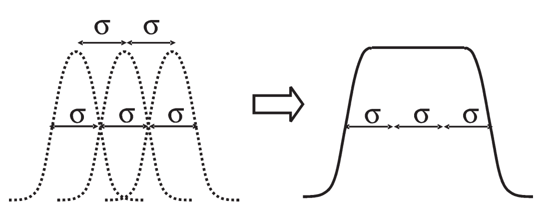

Fig. 2. The 3 × 2 arrangement, in which the peak separation is equal to the linewidth (σ) for each dot in a well, resulting in a flat-topped spectrum.

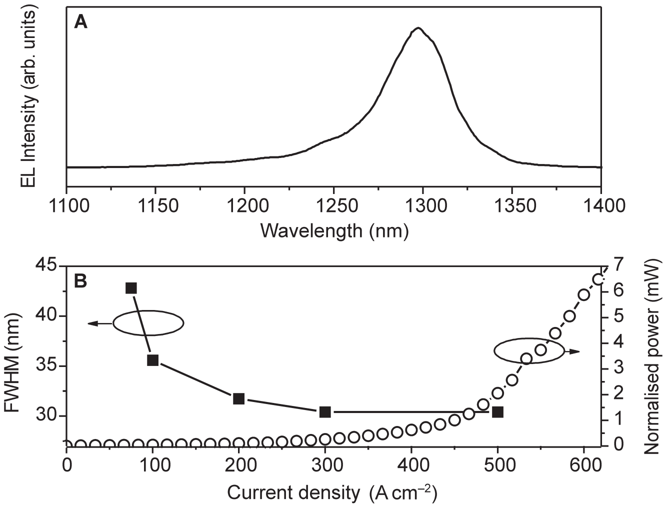

Fig. 3. Electroluminescence (EL) from a 6 mm dot-in-a-well superluminescent diode at room temperature and 100 A cm^{-2} (**A**). Power and full width at half maximum (FWHM) as a function of continuous current are also shown for this device (**B**).

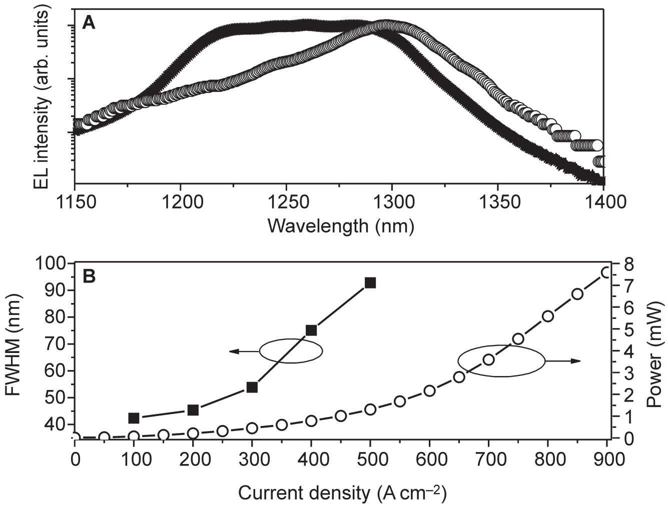

Fig. 4. Comparison of electroluminescence (EL) from a 3 × 2 superluminescent diode (solid) and a standard dot-in-a-well (open) for 500 mA (**A**). Power and full width at half maximum (FWHM) as a function of continuous current are also shown for the 3 × 2 device (**B**).

wavelength as a function of indium composition in the DWELL[6] to give indium compositions of 12%, 13.5% and 15%. Additionally, 12 acceptors per dot p-type modulation doping was employed.

Superluminescent light-emitting diodes were fabricated via a shallow ridge etch, with etching discontinued after removal of the upper p-doped GaAs and AlGaAs layers at a depth of 1.8 μm. Fifteen micrometer-wide ridges were misoriented by eight degrees to the facet normal. Contact bondpads were electroplated with approximately 2 μm of gold, and devices of 6 mm length and 15 μm width were mounted on ceramic tiles without anti-reflective coating.

Results and discussion

Electroluminescence spectra were captured from the front facet by an angled multimode fibre and measured with an Agilent 86146B optical spectrum analyser with a resolution of 0.06 nm. Figure 3 shows the electroluminescence spectrum measured from a 6 mm-long SLD with six identical 15% In_x DWELLs at room temperature and a continuous wave current density of 100 A cm^{-2}, together with the corresponding power-current response and FWHM linewidth measured from the electroluminescence spectra as a function of current. The electroluminescence spectra narrowed monotonously with increasing current as the ground state gain increased, with output powers in excess of 6 mW for FWHM of about 30 nm at 600 A cm^{-2}.

The flat-topped profile of the electroluminescence spectrum that resulted from the 3 × 2 DWELL, compared with the standard DWELL, for a drive current of 500 mA is demonstrated in Fig. 4. The linewidth broadened from about 30 nm for the standard DWELL to 95 nm for the 3 × 2 DWELL, where it appeared flat for a range of approximately 100 nm. The 95 nm FWHM was consistent with a theoretical 3σ prediction of 114 nm, confirming the success of our design realisation. The narrower FWHM was possibly due to absorption of longer wavelengths by the excited state of the quantum dots. As was the case for the DCMWELL in Ray *et al.*'s study,[7] the FWHM broadened with increasing drive current in contrast to the narrow-band DWELL SLD, as a result of the broader gain. Continuous wave output power of about 8 mW was recorded from this device. However, this higher power compared to the DWELL was a result of the incorporation of p-type modulation doping in the 3 × 2 arrangement, which was not included in the DWELL, and not the 3 × 2 arrangement itself.

Conclusions

A quantum dot SLD based on a 3 × 2 DWELL arrangement demonstrated high-power, broadband and a flat-topped emission spectrum with 8 mW continuous wave output power and 95 nm FWHM centred at 1 250 nm. Such a device may have application in frequency domain optical coherence tomography.

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1. Schmitt J.M. (1999). Optical coherence tomography (OCT): a review. *IEEE J. Sel. Top. Quantum Electron.* 5(4), 1205–1215.
2. Drexler W. (2004). Ultrahigh resolution optical coherence tomography. *J. Biomed. Opt.* 9(1), 47–74.
3. Lin C-F., Lee B-L. and Lin P-C. (1996). Broad-band superluminescent diodes fabricated on a substrate with asymmetric dual quantum wells. *IEEE Photon. Tech. Lett.* 8(11), 1456–1458.
4, McDougal S.D., Kowalski O.P., Marsh J.H. and Aitchison J.S. (1999). Broad optical bandwidth InGaAs–InAlGaAs light-emitting diodes fabricated using a laser annealing process. *IEEE Photon. Tech. Lett.* **11**(15), 1557–1559.
5. Rosseti M., Markus A., Fiore A., Occhi L. and Velez C. (2005). Quantum dot superluminescent diodes emitting at 1.3 μm. *IEEE Photon. Tech. Lett.* **17**(3), 540–542.
6. Liu H.Y., Hopkinson M., Harrison C.N., Steer M.J., Frith R., Sellers I.R., Mowbray D.J. and Skolnick M.S. (2003). Optimizing the growth of 1.3 μm InAs/GaAs dots-in-a-well structure. *J. Appl. Phys.* **93**(5), 2931–2936.
7. Ray S.K., Groom K.M., Beattie M.D., Liu H.Y., Hopkinson M. and Hogg R.A. (2006). Broad-band superluminescent light-emitting diodes incorporating quantum dots in compositionally modulated quantum wells. *IEEE Photon. Tech. Lett.* **18**(1), 58–60.