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Optical mode loss and gain of multiple-layer quantum-dot lasers

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Using an electrically pumped multisection technique, we have directly measured the internal optical mode loss of semiconductor-laser structures containing 1, 3, 5, and 7 layers of uncoupled InGaAs quantum dots. The optical loss does not increase with the number of dot layers so higher net modal gain can be achieved by using multiple layers. The maximum modal gain obtained from the ground state increases with dot layer number from 10 ± 4 cm^{-1} for a single layer to 49 ± 4 cm^{-1} for the 7 layer sample, which is typical of the threshold gain requirement of a 350 μm long device with uncoated facets. *© 2001 American Institute of Physics.* [DOI: 10.1063/1.1366652]

Recent results demonstrate that quantum dot active regions can be used to produce ultralow threshold current lasers with low temperature dependence of threshold current and emission at 1.3 μm using GaAs substrates (e.g., Refs. 1–4). However, the reduced density of states that facilitates the low transparency current and consequent low threshold current is accompanied by a smaller modal gain than is usual in a quantum well device. In applications demanding laser structures with larger losses—for short cavity lengths and where high reflection coating for the facets is not an option—the modal gain that can be obtained from a single layer of dots is insufficient. One possible solution is to incorporate multiple layers of dots to increase the modal gain, however, this will only be of benefit providing the optical mode loss does not also increase proportionately with the number of layers. Quantum dots by their nature introduce material inhomogeneity and extra surface area into the active region of the laser device and this could increase the optical losses. Furthermore, the extra confining layers in multilayer samples and the interfaces between these layers could also result in additional optical mode loss.

In evaluating multiple dot layers the accurate measurement of the mode loss is therefore as important as the measurement of the modal gain. The conventional method of determining the optical mode loss, α_i, from measurements of the external differential efficiency of devices of different length relies on the assumption that the quasi-Fermi levels are pinned above threshold.[5] This method may be inappropriate for quantum dot lasers and particularly so for multiple layer devices because it is not clear that the carrier density above threshold is pinned. In multiple layer quantum well devices, for example, it has been observed that carrier transport effects can lead to unequal populations in different wells and poor quasi-Fermi level pinning.[6]

In this work we directly measure optical mode loss and, independently, the net modal gain of structures employing 1, 3, 5, and 7 layers of quantum dots in which the thickness of the waveguide core of the laser is adjusted to maintain a constant average confinement factor per layer. We find that the optical mode loss does not increase as we increase the layer number and that the modal gain obtainable from the ground state increases from 10 ± 4 cm^{-1} for a single layer to 49 ± 4 cm^{-1} for the 7 layer sample.

The quantum dot laser structures consist of layers of $In_{0.5}Ga_{0.5}As$ deposited within 10 nm of GaAs at a growth temperature of 500 °C. For the multiple layer samples these GaAs layers are separated by 7 nm of $Al_{0.15}Ga_{0.85}As$. The rest of the waveguide core of the device is made up of $Al_{0.15}Ga_{0.85}As$ and the total waveguide core width is adjusted to maintain a constant average optical confinement factor per layer. This is calculated for two-dimensional layers containing the same volume of material as the quantum dots. The structures are clad with 1.2 μm wide, doped $Al_{0.60}Ga_{0.40}As$ layers. The quantum dot size and density are estimated from field-emission scanning electron microscopy measurements on an uncapped structure grown using similar conditions. A dot density of $(3\pm3)\times10^{10}\,\mathrm{cm}^{-2}$ and a dot diameter of ~20–25 nm are deduced. The structures are fabricated into 50 μm wide oxide isolated, multisection devices, as described in Refs. 7 and 8.

To assess the as-grown quantum dot structures we perform photoluminescence (PL) measurements. The wavelength of the peak of the photoluminescence spectrum at room temperature is given in Table I. The peak wavelength exhibits a shift to longer wavelengths with increasing layer number with the exception of the results for the 5 layer sample, which has a similar peak wavelength to the 3 layer sample. At low temperatures (≈10 K) the spectral widths reflect the inhomogeneous broadening due to dot size and

TABLE I. Summary of photoluminescence measurements on single and multilayer dot samples.

Sample	Wavelength of peak at room temperature/nm	Spectral width (FWHM) at 10 K/meV
1 layer	1045±2	67±1
3 layer	1063±2	49±1
5 layer	1060±2	38±1
7 layer	1070±2	32±1

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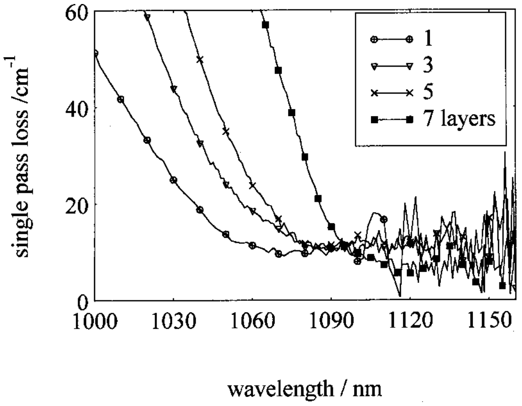

FIG. 1. The total modal loss spectra for samples with 1 layer (circles), 3 layers (triangles), 5 layers (crosses), and 7 layers (squares) of dots. At long wavelengths the absorption is negligible and the constant amplitude part of the spectrum yields the value of α_i.

shape fluctuations. The spectral widths [full width at half maximum (FWHM)] reduce from 67±1 meV for the single layer sample to 49±1 meV for the 3 layer sample to 38 ±1 meV and 32±1 meV for the 5 and 7 layer samples. The shift of the spectral peak and narrowing of the spectral width with increasing layer number has previously been attributed to either electronic coupling of dots in different layers[9] or to improved dot shape uniformity in multilayered samples due to surface strain from the initial layer of dots altering the dot formation kinetics.[10] The large separation of dot layers in our samples, 10 nm of GaAs and 7 nm of $Al_{0.15}Ga_{0.75}As$, leads us to believe that the dots are unlikely to be electronically coupled and that the shift in wavelength and linewidth narrowing is due to improved dot uniformity.

The spectrum of the total modal loss (dot self-absorption and α_i) is measured using the single pass, multisection method[7] and is shown in Fig. 1 for each of the multilayer samples. The part of the spectrum exhibiting absorption from the quantum dots shifts to longer wavelengths as the number of dot layers is increased in agreement with the PL data of Table I. The value of α_i is determined from the part of the spectrum unaffected by absorption in the quantum dots, where the loss is independent of wavelength. α_i values of (11±4) cm^{-1}, (11±2) cm^{-1}, (11±2) cm^{-1}, and (7±2) cm^{-1} are determined from this region of the loss spectrum for the 1, 3, 5, and 7 layer samples, respectively. The inclusion of extra layers of dots (and the wells in which they are embedded) and the corresponding increase in the number of interfaces does not lead to an increase in the measured loss. This supports calculations that predict that loss due to scattering by quantum dots can be small ($\approx$1 cm^{-1} for the size and density of dots in our devices)[11] and also indicates that scattering at the interfaces between GaAs and $Al_{0.15}Ga_{0.85}As$ in these samples does not lead to appreciable loss. Another loss mechanism that is the same for each structure, such as free carrier absorption in the doped cladding layers, must dominate the measured optical loss.

Having measured the value of α_i we determine the net modal gain by using the multisection device method[1] for the different dot laser structures. We find that for higher layer number samples the gain is generated by the quantum dot states, whereas for the single layer device at the highest current densities the gain originates from wetting layer states.

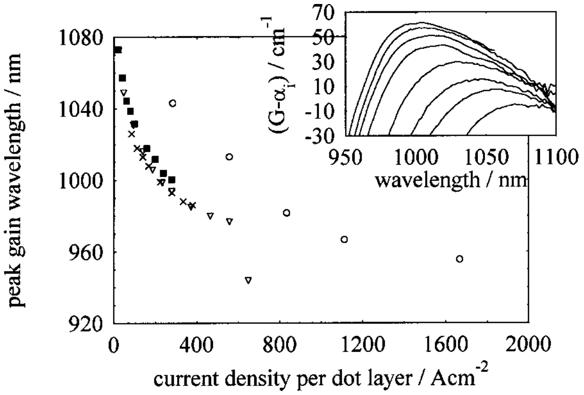

FIG. 2. The wavelength of the peak of the gain spectrum vs the current density per layer for samples with 1 layer (circles), 3 layers (triangles), 5 layers (crosses), and 7 layers (squares) of dots. The inset shows the net modal gain spectra as a function of wavelength for the 7 layer structure with applied currents of 140, 278, 556, 834, 1112, 1668, and 1890 A cm^{-2}.

Figure 2 is a summary of the measured values of the wavelength of the peak of the gain spectrum as a function of current density per layer. The inset of Fig. 2 is an example of the net gain spectra, used to evaluate the peak wavelength, obtained from the 7 layer sample and plotted for total current densities (300 μm geometrical length and a width of 60 μm, which took account of current spreading) between 140 and 1890 A cm^{-2}. As we have previously observed for a single dot layer sample,[8] the peak of the net gain spectrum moves continuously to shorter wavelengths with increasing current injection. The continuous nature of the shift is a consequence of the inhomogeneous broadening of the dot states, which is reflected in the shape of the gain spectra. The ground state, excited state, and wetting layer are not particularly well defined in the gain spectra of any of the devices studied here due to the inhomogeneous broadening. For the single dot layer sample the peak of the gain spectrum shifts from 1044 to 956 nm as the current density is increased from 280 to 1668 A cm^{-2} and this corresponds to a movement from the broadened ground state of the quantum dots to an excited state and finally to the wetting layer at the highest current densities.[8] Peak gain is observed over a narrower range of wavelengths for the multilayer samples. For example in the case of the 7 layer sample the peak moves from 1070 nm at a current density of 140 A cm^{-2} (=20 A cm^{-2} per layer) to 1003 nm at a current density of 1890 A cm^{-2} (=270 A cm^{-2} per layer). This and the fact that, in the inset of Fig. 2, there is an absence of gain at wavelengths corresponding to the wetting layer is presumably because of the lower carrier density in states corresponding to these wavelengths for the 7 layer sample. Wetting layer gain is also absent from the 5 layer data and only apparent at the highest injection levels for the 3 layer sample. The abrupt step in peak gain wavelength for the 3 layer sample at a current density per layer of approximately 600 A cm^{-2} reflects the movement of the peak gain from the dot excited states to the wetting layer. In the single layer sample wetting layer gain was also apparent at high current densities.[8]

Adding dot layers increases the modal gain obtained from the dots and reduces the effect of the wetting layer for the same injection current density. The gain-current characteristics for all the samples are plotted in Fig. 3. These are in

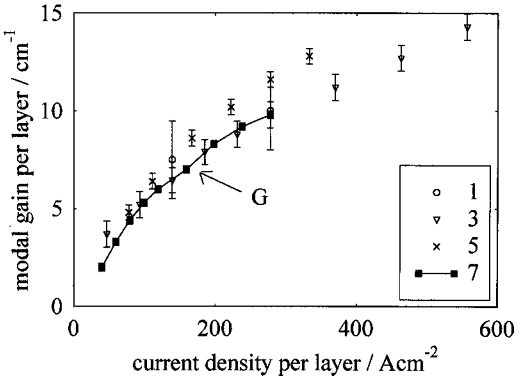

FIG. 3. The modal gain per layer vs current density per layer for samples containing 1 layer (circles), 3 layers (triangles), 5 layers (crosses), and 7 layers (squares) of dots. The error bars reflect the uncertainty arising from the measurement of net modal gain and modal loss and the results are the average of measurements taken on two devices of each layer number.

the form of peak modal gain per layer versus current density per layer to allow direct comparison of results for the different structures. Since the data of Fig. 1 suggest that the optical mode loss does not scale with the number of layers we first add the measured mode loss in each case to the net modal gain (gain-mode loss) measured in the experiment and shown for the 7 layer sample in the inset of Fig. 2. The modal gain per layer, which is plotted on the ordinate, is then the gain per layer available to overcome the total optical losses per layer. For example, a device with an optical mode loss of 11 cm^{-1} and a length of 225 μm with uncoated facets (mirror loss = 55 cm^{-1}) would operate at the top end of the 7 layer gain-current characteristic (gain per layer = 9.4 cm^{-1}), and as we have shown earlier for this sample these values of gain are obtained from the quantum dots. While focused on the 7 layer data (squares) it is worth noting that an inflection in the curve is apparent at the point marked G. This provides some evidence of a transition from the saturated, inhomogeneously broadened ground state gain to inhomogeneously broadened excited state gain. This places the maximum gain obtainable from the ground state at a value of approximately 49 cm^{-1} or 7 cm^{-1} per layer, which is of the same order as the gain obtained from the single layer of dots of 11 ± 4 cm^{-1}.[8] A 350 μm long device with uncoated facets and an internal optical mode loss of 11 cm^{-1} (total loss = 46 cm^{-1}) would operate on the dot ground state.

In general terms the results of Fig. 3 illustrate that the modal gains per layer at the same current densities per layer are similar for the different layer number samples. This is particularly true at low current density, corresponding to ground state operation, and confirms the fact that adding layers simply proportionately increases the ground state gain. At larger current density the 5 layer sample shows evidence of slightly higher gain per layer than the other samples, which may be consistent with the different peak emission wavelength observed in the PL measurements. The observed reduction in PL linewidth as the layer number increases does not appear to have had a significant affect on the gain-current relation.

In summary we have measured the internal optical mode loss and modal gain of quantum dot lasers containing 1, 3, 5, and 7 layers of quantum dots. The optical mode loss did not increase as the layer number increased whereas the modal gain obtainable from the dot ground state increased from 11 ± 4 cm^{-1} for the single layer sample to 49 ± 4 cm^{-1} for the 7 layer sample.

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