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Modal gain and internal optical mode loss of a quantum dot laser

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The modal gain spectra and internal optical mode loss of a semiconductor laser structure containing a single layer of InGaAs quantum dots have been measured independently and directly as a function of current density. The quantum dot gain exhibits no obvious polarization dependence. The maximum modal gain of (11 ± 4) cm^{-1} obtained from the ground state of a single layer of quantum dots is in this case insufficient for lasing operation since the internal optical mode loss measured on the same sample is (11 ± 4) cm^{-1}. As expected laser emission is not observed from the dot ground state, but from the excited dot state or from the wetting layer depending on device length. © *2000 American Institute of Physics.* [S0003-6951(00)00428-9]

Semiconductor lasers containing quantum dots as active layers are of considerable interest due to the improved device performance that the discrete density of states of such layers may offer.[1] However, the small overlap between the gain producing region and the optical mode, due to the small size and finite separation of the quantum dots, can lead to less maximum modal gain compared to that of a quantum well device. This is not necessarily detrimental providing the modal gain (G) is sufficient to overcome the optical losses (internal optical mode loss and mirror loss) in a particular device design but it makes the assessment of both optical gain and optical losses critical in quantum dot structures.

There are several techniques routinely employed to measure or deduce gain in quantum wells (see, e.g., Refs. 2–4), but there are difficulties associated with these, particularly when used with quantum dot structures. The main shortcoming of most gain measurement techniques is that a measurement of the optical losses is required to calibrate the gain values. The measurement usually used to derive the internal optical mode loss (α_i) relies on the assumption that the internal differential efficiency is constant for devices of different length.[5] This assumption is particularly difficult to justify for quantum dot structures where recombination occurs from different dot states and even the wetting layer as the device length and hence threshold gain requirement is changed.

Spontaneous emission spectra may be transformed to gain spectra providing the carriers are in thermodynamic equilibrium.[4] Such an assumption may not be valid for quantum dot structures where carriers can be spatially isolated in different sized dots, although there are some preliminary results that indicate that this approach may be satisfactory in some dot structures, at least at higher ($\approx>300$ K) temperatures.[6]

Here we describe independent measurements of the optical gain and α_i on the same structure using a single pass, electrically pumped multisection technique.[7] For the single layer structure investigated the measured dot ground state modal gain is only sufficient to match the measured value of α_i, therefore we do not expect lasers fabricated from this material to exhibit lasing action at wavelengths corresponding to the ground state and find that this is indeed the case.

The quantum dot laser structure consists of a single, eight monolayer, $In_{0.5}Ga_{0.5}As$ layer deposited within 10 nm of GaAs at a growth temperature of 500 °C. The GaAs is positioned symmetrically within a 190 nm $Al_{0.15}Ga_{0.85}As$ intrinsic region and the structure is clad with doped $Al_{0.60}Ga_{0.40}As$ layers. The quantum dot size and density can be estimated from field-emission scanning electron microscopy measurements on an uncapped structure grown using similar conditions. A dot density of $(3\pm3)\times10^{10}$ cm^{-2} and a dot diameter of ~20–25 nm were deduced, which are consistent with the observations of Solomon *et al.*[8] The structure was fabricated into 50 μm wide oxide isolated stripe lasers 450–1500 μm long and also into multisection devices, as described in Ref. 7.

The spectrum of the total modal loss (dot absorption and α_i) is shown in Fig. 1. The value of α_i is determined from the part of the spectrum unaffected by absorption in the quantum dots. The photovoltage absorption spectrum[9] of Fig.

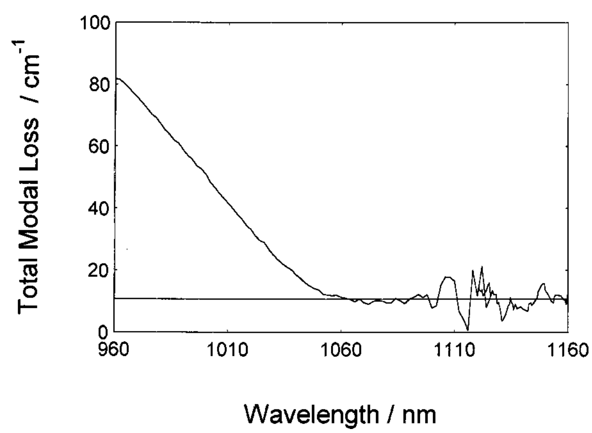

FIG. 1. Total modal loss spectrum. At long wavelengths the absorption is negligible and the constant amplitude part of the spectrum yields the value of α_i. The horizontal line is a guide to the eye.

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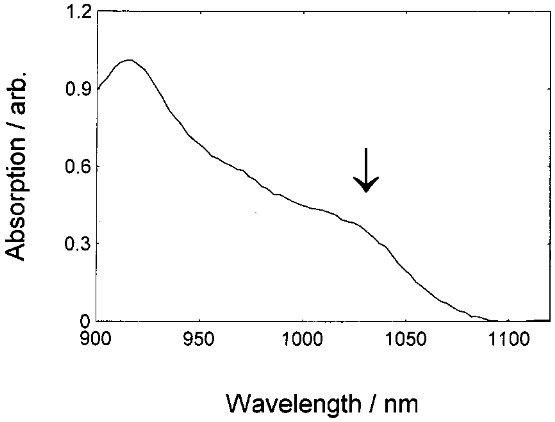

FIG. 2. Edge photovoltage absorption spectrum (Ref. 9). The inhomogeneously broadened dot ground state is marked by an arrow. The absorption is negligible beyond 1070 nm.

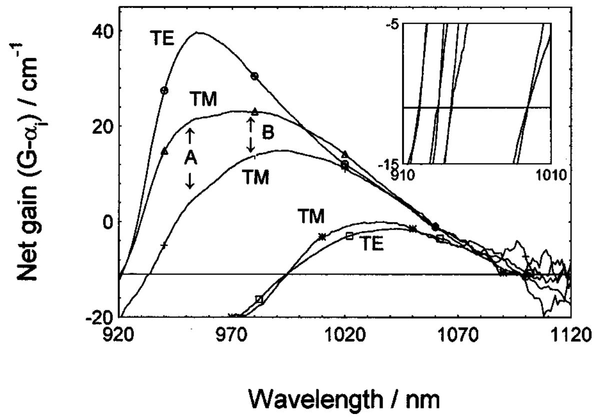

FIG. 3. TE and TM net modal gain spectra as a function of wavelength at injection levels of 278 (squares and stars) and 1668 A cm^{-2} (circles and triangles). Another TM spectrum is plotted for an injection level of 1112 A cm^{-2} (crosses). In the two highest injection TM spectra two features at A and B are apparent and these correspond to the wetting layer and dot excited state, respectively. The inset shows, in detail, the region of the spectra where the TE and TM gain crossover with additional data for TE (1112 A cm^{-2}) and TE and TM spectra (834 A cm^{-2}). The solid horizontal line is a guide to the eye.

2 shows that the absorption from the quantum dots is negligible beyond 1070 nm. An α_i value of (11 ± 4) cm^{-1} is determined from this region of the loss spectrum of Fig. 1, where the loss is independent of the wavelength. The experiment works in quantum well devices because we have a source of light in the section under electrical injection at wavelengths below the absorption edge of the unpumped material due to carrier induced band gap narrowing.[7] The wavelength independent section of the spectrum of Fig. 1 is evidence that there is also sufficient band gap narrowing in quantum dots. However, there is a larger uncertainty (standard error of mean of data 1070–1160 nm) in this result than we have typically found for quantum well devices due to lower light emission at the longer wavelengths, presumably because there is less band gap narrowing in a quantum dot structure. The band gap narrowing that does occur could be due to the effect of carriers in the wetting layer.[10]

Having independently measured the value of α_i we determined the net modal gain by using the multisection device method for both transverse electric (TE) and transverse magnetic (TM) polarizations. The modal gain is determined by measuring the amplified spontaneous emission (ASE) emerging from a single electrically pumped 300 μm long section and comparing it with that from multiple, electrically pumped 300 μm sections. The optical mode should grow exponentially as it travels along the 300 μm sections. For sections of some larger length or when the total length is large we would expect that the optical mode would no longer be able to grow exponentially due to limitations to the rate at which carriers can recombine, the phenomenon that results in spatial hole burning. To confirm that it is not affecting our results, taken with 300 μm long sections, we have repeated the measurements, increasing the length and number of sections. Using two 600 μm long sections we find that the resulting gain spectra are unaltered, even for the highest current densities.

Although the laser emission of all our oxide stripe devices is TE polarized, the TM gain data are useful since the wetting layer emission is reduced in these spectra allowing us to observe excited dot state emission. Net modal gain spectra for the TE and TM modes are shown in Fig. 3. At a current density of 278 A/cm^2 the TE and TM spectra are similar and the net gain peak occurs at the same wavelength as the feature at 1030 nm in Fig. 2 corresponding to the inhomogeneously broadened dot ground state. At the highest current density and at short wavelengths the TE and TM spectra are different. The TE spectrum is dominated by emission at a wavelength of 950 nm (A) corresponding to the electron to heavy hole transition (e–hh) in the quantum well-like wetting layer. According to the polarization selection rules for a quantum well the TM spectrum should only show evidence of electron to light hole transitions (e–lh), which are at shorter wavelengths than the electron to heavy hole transitions in unstrained or compressively strained material.[9] Indeed the TM spectrum shows less of the e–hh emission at 950 nm (A) and it is possible to detect a second peak at 970 nm (B). We believe that this second peak can only correspond to a dot excited state since any electron (e–lh) transition in the wetting layer would be detected below 950 nm. The second peak is also apparent in the TM spectra at an intermediate current density. Overall the data of Fig. 3 exhibit a polarization dependence at wavelengths corresponding to the wetting layer but no polarization dependence where the gain is produced by the quantum dots.

In Fig. 4 the TE net modal gain spectra for the same sample at a series of current densities (278–1668 A/cm^2) are plotted. The maximum value of the peak of the net gain spectrum at wavelengths corresponding to the ground state is approximately zero. The modal gain from the single layer of dots is therefore (11 ± 4) cm^{-1} $(=\alpha_i)$. This means that the ground state transition (of a single layer of quantum dots) in this device does not provide enough modal gain for lasing operation $(=\alpha_i+$mirror loss). The wavelength of the net gain peak shifts from 1025 to 950 nm as the current density is increased, corresponding to movement from the ground state of the quantum dots to an excited state and finally to the wetting layer at the highest current densities. The gain spectra of Fig. 4 allow us to make predictions about the performance of lasers fabricated from this material. We would expect to achieve TE polarized laser emission at wavelengths corresponding to the excited dot states and the wetting layer

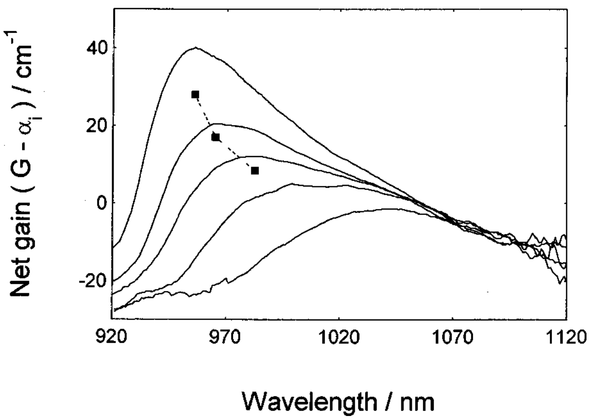

FIG. 4. Net modal gain spectra as a function of wavelength for the TE mode with applied currents of 278, 556, 834, 1112, and 1668 A cm^{-2}. The calculated mirror loss and measured lasing wavelength for devices 450, 750, and 1500 μm in length are represented by closed squares.

and not from the ground state. The wavelength of laser emission of devices of decreasing cavity length should decrease as the threshold losses and required threshold gain increase.

We have measured the room temperature lasing wavelength of oxide stripe devices of different cavity length using a spectrum analyzer. The devices were pulse driven with a pulse length of 1 μs, a duty cycle of 0.1%, and an applied current of $1.05\times I_{th}$ and all produced TE polarized laser emission. Devices of lengths 450, 750, and 1500 μm, with corresponding threshold current densities of 1067, 630, and 450 A cm^{-2}, respectively, produced spectra with peak lasing wavelengths of 956 (450 μm), 965 (750 μm), and 982 nm (1500 μm). Using refractive index data for AlGaAs (Ref. 11) and the Fresnel equations to determine the mirror reflectivity, $R=0.29$, for devices 450, 750, and 1500 μm in length we obtained mirror loss values of 28, 17, and 8 cm^{-1}, respectively. The calculated loss and lasing wavelength values are marked by closed symbols in Fig. 4 and follow the net gain data.

As predicted, we did not obtain lasing from the ground state. The lasing wavelength did decrease with decreasing cavity length and the values are in agreement with those determined from the net gain data and the calculated losses. The 1500 μm long device lased at a wavelength that corresponds to the dot excited state, changing to a wavelength corresponding to the wetting layer for the 450 μm long laser.

It is also possible to extract values of α_i from these gain spectra, which we can compare to the independently measured value in Fig. 1. At extremely long wavelengths where the gain tends toward zero the net gain value should tend toward α_i. At shorter wavelengths, providing the carriers producing TE and TM emission are in thermal equilibrium, the TE and TM spectra should cross at the transparency point (net gain$=\alpha_i$).[7] The value of α_i determined from the point at which the TE and TM spectra cross is also marked in Fig. 3 and appears to be constant, within experimental uncertainty, at different injection levels and at different wavelengths. This line also falls within the uncertainty of the α_i value determined from extrapolation of the net gain to long wavelengths in Fig. 4. These values are consistent with the value obtained from Fig. 1 and provide some evidence that carriers in different dots in this structure at 300 K are in thermal equilibrium.

From this work it is clear that the value of α_i is a critical performance parameter in dot structures because the value is similar to the modal gain and therefore, to properly quantify the performance of quantum dot lasers, it is necessary to accurately measure both the optical gain and the internal optical mode loss. Using a multisection device method we have shown that a semiconductor laser with one layer of InGaAs quantum dots provides a maximum ground state peak gain of 11 cm^{-1}. This is insufficient to overcome the measured internal optical mode loss of 11 cm^{-1} and as such we do not expect lasing operation from the ground state even for extremely long devices. Indeed, at $T=300$ K devices lase in the TE mode from the dot excited states or the wetting layer, depending on device length, but not from the dot ground state. Our results illustrate the critical balance between gain and loss in quantum dot lasers and show that, when designing and growing quantum dot lasers, emphasis should be placed on both increasing the gain and reducing the optical losses.

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