Energy distributions of carriers in quantum dot laser structures

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ABSTRACT

Using the segmented contact method, we have measured the passive modal absorption, modal gain and spontaneous emission spectra of an InAs "dot-in-well" (DWELL) system where the inhomogeneous broadening is sufficiently small that the ground and excited state transitions can be spectrally resolved. The modal optical gain from the ground state saturates with current at a maximum value of one third of the magnitude of the measured absorption. The population inversion factor spectrum, obtained from the measured gain and emission spectra, shows that the carrier distributions cannot be described by a single global Fermi distribution. However, the inversion factor spectrum can be described by a system where the ground state and excited state occupancies are each described by a Fermi distribution but with different quasi-Fermi energy separations.

Keywords: quantum dots, quantum dot lasers, optical gain, gain saturation.

1. INTRODUCTION

With careful design, it possible to use quantum dot structures to make semiconductor diode lasers with very low threshold current densities. The maximum modal gain which can be obtained from a fully inverted dot system is small compared with quantum wells and lies in the region of 3 to 10 cm^{-1} per layer depending on the dot density (typically in the range 10^{10} to 10^{11} cm^{-2}) and the low thresholds are achieved by minimising the optical waveguide loss (α_i) and the distributed mirror loss, and by using several layers of dots. Further refinements such as the use of "dot-in-well" (DWELL) structures have led to threshold current densities as low as J_{th} = 26 Acm^{-2} at a lasing wavelength of 1.25 μm[1] using long cavity devices (7.8mm).

Despite this progress, the manner in which the localised dot states are occupied by electrons under lasing conditions is not well understood. It has been shown that in some cases at room temperature the occupation of dot states of different energy can be described by Fermi Dirac probability distribution in energy with a global Fermi level[2], possibly because of the strong interaction of the dot states with the extended states of the wetting layer. From this standpoint the wetting layer may play a valuable role in maintaining a spatially uniform dot state occupancy. On the other hand, there is evidence that the high density of states at higher energies, associated with excited states or the wetting layers, itself serves to make it difficult to populate fully the ground state of the dot system[3], even under quasi-equilibrium conditions. An understanding of the energy distribution of electrons is important in obtaining the maximum available gain from a system of dots.

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We have investigated these effects at room temperature in a DWELL structure using the segmented contact method to measure the passive modal absorption, the modal gain, inversion factor and spontaneous emission spectrum. These measurements enable us to compare the magnitude of the passive modal absorption with the magnitude of the modal gain and by combining gain and spontaneous emission spectra the population inversion factor spectrum can be determined and compared with that predicted for a thermal distribution giving insight into the energy distribution of carriers. In the structures used the ground and excited states can be clearly distinguished even under high injection conditions, due to the low inhomogeneous broadening and reasonably deep confining potential.

2. EXPERIMENTAL DETAILS

The sample was grown by MBE and comprised layers of InAs dots embedded in a $In_{0.15}Ga_{0.85}As$ well of thickness 9.6nm and surrounded by un-doped GaAs to provide a waveguide core of total thickness 230nm[4]. The cladding layers were $Al_{0.7}Ga_{0.3}As$. The material was processed into 100μm wide oxide-isolated devices with the contact separated into segments each 293μm long in a device of overall length 3mm. These devices were mounted onto copper heatsinks. The contact segments were driven separately with pulses of 1μs duration at a duty cycle of 0.1%. The amplified spontaneous emission was collected from the facet of the structure and detected using a grating spectrometer and a Hamamatsu cooled photomultiplier sensitive out to a wavelength of 1.4μm.

The method by which the modal absorption, modal gain and spontaneous emission spectra are obtained from analysis of edge-emitted amplified spontaneous emission (ASE) spectra is given in ref[5]. The passive absorption of the gain material is measured by observing emission when the first and second segments are driven separately, the light from the second segment being passively absorbed by the first segment before being detected. The gain is measured by driving section one, then section one and two together and so on, to replicate a stripe-length determination of modal gain[6]. All measurements are for light polarised in the plane of the layers of the structure (TE).

3 RESULTS

The measured passive net modal absorption spectrum for light propagating along the waveguide containing the layer of dots, measured with a drive current through the exciting segment of 100mA, is shown in figure 1. Absorption at photon energies below the main absorption edge is due to scattering losses in the waveguide which amount to about 5±1 cm^{-1}. This is a larger value than that obtained from an analysis of the differential efficiency as a function of cavity length[7]. The absorption peaks at 1.02eV and 1.08eV are due to the ground and excited states of the dot system and the modal absorption at each peak attributable to the dots is 30±1 cm^{-1} and 56 ±1 cm^{-1} respectively (ie, after correction for the waveguide loss).

The net modal TE gain is shown in figure 2 for currents per segment between 20mA and 200mA; the passive absorption spectrum is also shown. The "gain" at low photon energy below the absorption edge tends to a similar value to the absorption spectrum, confirming the value obtained for the waveguide loss. As the current is increased the ground state gain tends toward saturation at currents above about 100mA (340 Acm^{-2}) and the ground state peak modal gain (after correction for the waveguide loss) is about 8±1 cm^{-1}. The modal gain determined from measurements of threshold current as a function of cavity length is about 12.5 cm^{-1} [1,4] for a current density of 200 Acm^{-2}. In both cases the maximum ground state gain is significantly less than the measured ground state absorption, by a factor 2 or 3.

The uncalibrated experimental data for true spontaneous emission spectra in fig 3 show four transitions below the transition energy of the well at 1.25 eV. The ground state emission saturates with increasing current at a value of about 160 mA .

Figure 4 shows uncalibrated data for the population inversion factor obtained as the measured modal gain (G) divided by the uncalibrated spontaneous emission (I_{spon}) at each photon energy:

$$P_F(h\nu) = \frac{G(h\nu)}{I_{spon}(h\nu)} \qquad (1)$$

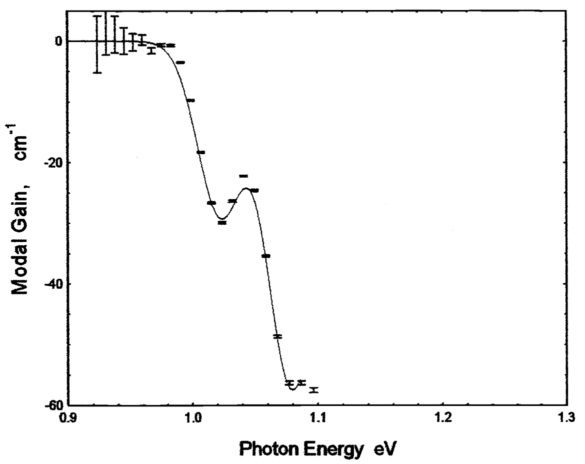

Figure 1. Measured modal absorption spectrum (being negative gain). (Corrected for waveguide loss)

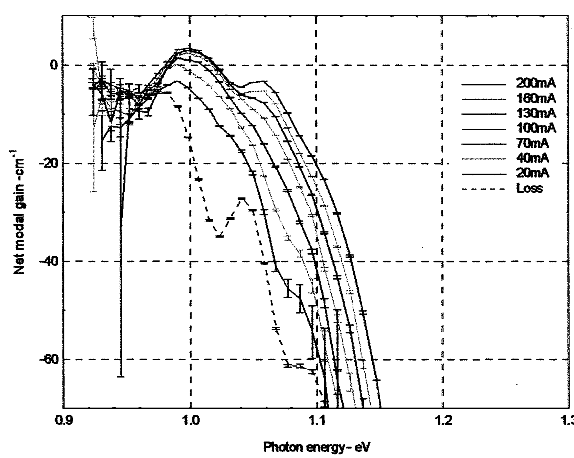

Figure 2. Measured modal gain spectra for drive currents per segment from 20mA to 200mA.

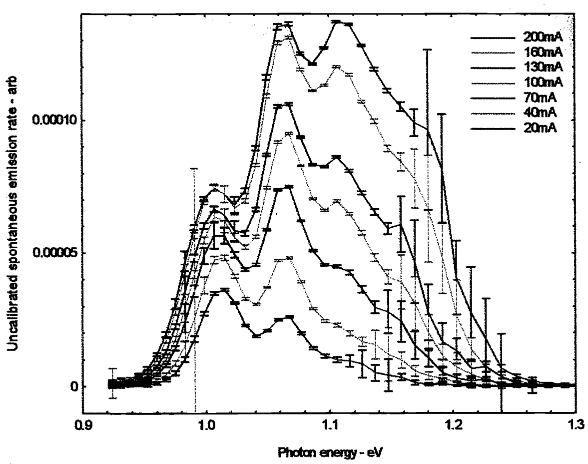

Figure 3. True spontaneous emission spectra derived from analysis of edge emitted ASE spectra.

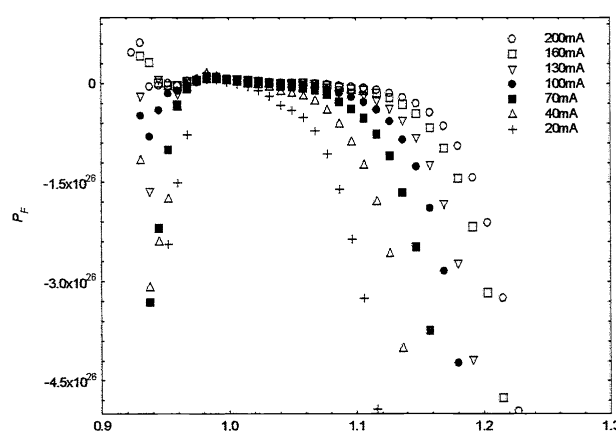

Figure 4 Spectra of the measured population inversion factor obtained from experimental data using equation (1).

4 ANALYSIS OF INVERSION FACTOR

The population inversion factor is related to probabilities of occupation by electrons of the upper and lower energy states (f_1 and f_2 respectively) which participate in a transition at photon energy $h\nu$:

$$P_F(h\nu) \propto \frac{f_1 - f_2}{f_1(1 - f_2)} \tag{2}$$

The constant of proportionality includes an unknown calibration factor for the measured spontaneous emission rate. The inversion factor tends to $-\infty$ at high photon energy where the upper state is empty and the lower state full, and to +1 at small photon energy where the system is fully inverted such that the upper state is completely full (f_1 = 1) and the lower state completely empty (f_2= 0). P_F also tends to +1 when, *either* $f_1 = 1$ *or* $f_2 = 0$, with the other respective occupation factor taking any value between 0 and 1. P_F crosses zero at the transparency point.

Although the experimental data is in arbitrary units, these features are apparent in the spectra in figure 4, where P_F decreases with increasing photon energy and increases with increasing drive current. We also observe that the values of P_F for different drive currents converge to a common value at low photon energy and this is to be expected when the system becomes fully inverted, or when the occupation of one or both states saturates before reaching their limiting values. At the ground state gain peak (1 eV) the gain saturates with current above 100mA, as does the spontaneous emission within the error bars, so we conclude that above this current the occupation factors have saturated for the ground state, though comparison of absorption and gain spectra shows that the ground state is not fully inverted. We conclude that either $f_1 < 1$ and $f_2 = 0$, or $f_1 = 1$ and $f_2 > 0$, or the system saturates with both f_1 and f_2 constant at values between 0 and 1. In the first two cases equation (2) takes the value unity, but is undetermined in the third case.

These remarks apply to any pair of occupation factors for the upper and lower states which can be globally defined throughout the sample as a function of energy. In the specific case that the system adopts a quasi-equilibrium distribution defined by a global Fermi-Dirac (F-D) function the inversion factor becomes:

$$P_F \propto \left\{1 - \exp\left(\frac{h\nu - \Delta E_f}{kT}\right)\right\} \tag{3}$$

where ΔE_f is the separation of the quasi-Fermi levels specifying the occupancy of the upper and lower states. Figure 5 shows equation (3) superimposed on the experimental data of figure 4 where the quasi-Fermi level separations have been chosen to correspond to the transparency points of the experimental data. The data has been scaled such that P_F tends to unity at low photon energy (though this may not actually be the case). There is good agreement between equation (3) and the data at low current where only the ground state is populated, however at 100mA this agreement only extends to a photon energy of about 1.03eV and at higher values, where the excited state begins to contribute, the measured P_F is greater than the F-D value . At 200mA there is only agreement at low photon energy where the gain is saturated.

Equation (2) is based upon a simple two-level model, however it can be shown that even when more than one transition contributes to the gain and emission, the behaviour of the inversion factor follows that of equation (3) when all states are in quasi-equilibrium defined by a common quasi-Fermi level separation. Thus contributions from multiple transitions in a system which is in overall equilibrium does not explain why our data does not match the Fermi-Dirac expression (3) and we conclude from figure 5 that this dot system cannot be described by a universal Fermi-Dirac distribution. However, an inspection of the spectra in figures 4 and 5 suggests that in regions where only one transition is dominant the data can be represented by a Fermi-Dirac distribution with equation (3).

To verify that the data can be represented in this way we have calculated the inversion factor for inhomogeneously broadened ground and excited state distributions with different quasi-Fermi energy separations using inhomogeneous broadening parameters obtained from the passive absorption spectrum. The parameters used in the calculations were those for InAs where the matrix element, M, is given by $2|M|^2/m_0$=21.1eV, and the overlap envelope integrals in the dots were taken as unity. We assumed that the inhomogeneous broadening (given by a Gaussian distribution, *B*) is much greater than the homogeneous broadening (given by a Lorentzian, *L*) and obtained a good description of the absorption spectrum with a Lorentzian linewidth of Λ=21μeV, (corresponding to a 200ps dephasing time), an inhomogeneous linewidth of the ground state of σ= 16 meV and σ=18meV for the excited state. This increase in σ was necessary to fit the absorption edge of the 1st excited state and is expected for higher dot states, as they are more sensitive to variations of size and composition[8].

We have calculated the population inversion spectrum for three transitions assuming that the occupancy of states within the ground state distribution and those within the excited state distribution are each independently described by a Fermi-Dirac function but with different quasi-Fermi energy separations:

$$P_F(h\nu) = \frac{\sum_{j=1-3} \int |M|^2 B(E_i, \sigma_j) L(h\nu - E_i, \Lambda) [f_1(E_i, \Delta E_{fj}) - f_2(E_i, \Delta E_{fj})] dE_i}{\sum_{j=1-3} |M|^2 B(E_i, \sigma_j) L(h\nu - E_i, \Lambda) [f_1(E_i, \Delta E_{fj}) \{1 - f_2(E_i, \Delta E_{fj})\}] dE_i} \tag{4}$$

To determine the Fermi functions it is necessary to assign values to the two individual quasi-Fermi energies and this was done by setting the quasi Fermi energies such that the lower state is empty of electrons, ie f_2 =0, assuming that it is the upper states which are not full populated achieve complete inversion at high injection. (The inverse situation, ie the upper states fully populated and the lower states partially empty, gives very similar results.) The values of quasi Fermi energy separation used to match the spectrum measured at 200mA were 1.04 eV for the ground state, 1.06eV and 1.10eV for the first and second excited states respectively. The agreement between the calculation from equation (4) and experimental results shown in figure 6 is very good.

We conclude that in this dot system, the ground state and excited state carrier populations are not in quasi equilibrium with each other, but they can be individually described by Fermi-Dirac distributions with the quasi-Fermi energy separation for the first excited state being 20 meV greater than for the ground state.

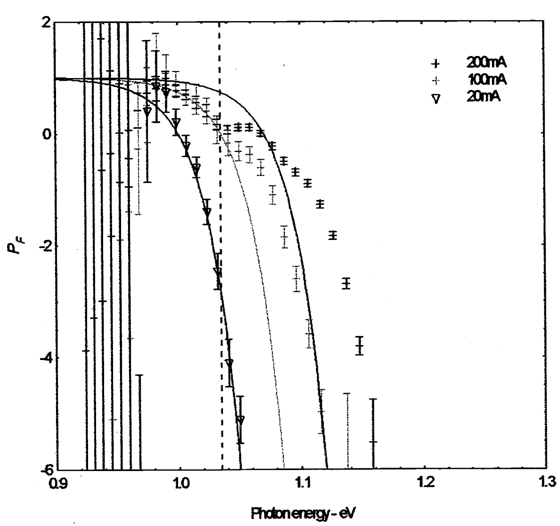

Figure 5. Experimental data for the inversion factor compared with calculated spectra assuming a Fermi Dirac distribution.

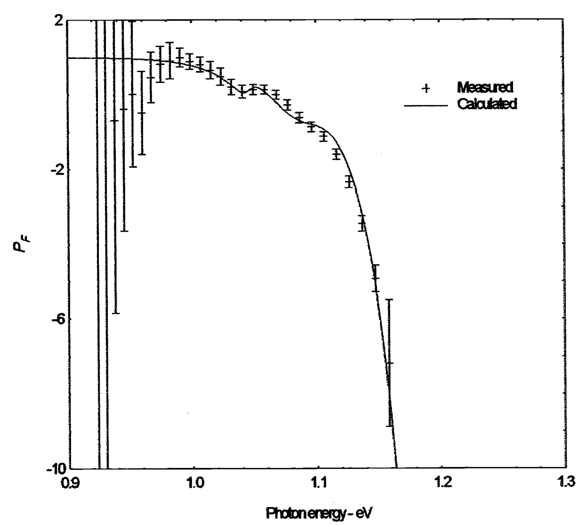

Figure 6. Measured and calculated (equation 4) inversion factor spectra for a current of 200mA per segment.

5. DISCUSSION

Figure 6 shows that the carrier distribution in this *particular* quantum dot system can be *described* by a model in which the occupancies of the ground and excited states are not in overall equilibrium but can each be described by a quasi-equilibrium Fermi-Dirac distribution with different appropriate Fermi energy separations. If this is indeed the case, the occupation of the localised, spatially-separated states within the inhomogeneous distribution of *ground* states are in global quasi-equilibrium and the occupation of spatially-separated states within the inhomogeneous distribution of *excited* states are similarly in global quasi-equilibrium. It may be that photon mediation between dots is important in establishing this particular situation because in these structures the inhomogeneous distributions of ground state and excited state transitions hardly overlap so there is little photon interaction between them though the ground and excited states can individually interact within the homogeneous linewidth.

6 SUMMARY

We have measured the passive modal absorption, modal gain and spontaneous emission spectra in a quantum dots system where the inhomogeneous broadening is sufficiently small that the ground and excited state transitions can be spectrally resolved. The optical gain from the ground state saturates with current at a value which is about one third of the magnitude of the measured ground state absorption. The measured population inversion factor cannot be described by a single global Fermi distribution. However, we find that the inversion factor can be described by a system where the ground state and excited state occupancies are each described by a Fermi distribution but with different quasi-Fermi energy separations.

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