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# Long wavelength quantum-dot lasers selectively populated using tunnel injection

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**Abstract**
Using measured amplified spontaneous emission data, we have derived and analysed the carrier distribution of a five-layer tunnelling injection quantum-dot structure at temperatures of 300 K and 350 K. The results are consistent with the direct injection of electrons from the injector well into a subset of lower energy dot states. The carrier distribution spectra contain features which suggest that dots of a particular size within the ensemble are preferentially populated leading to a reduced spectral broadening of the emission.

(Some figures in this article are in colour only in the electronic version)

## 1. Introduction

Lasers containing self-assembled quantum dots (QDs) have developed rapidly to display lower threshold current densities, reduced temperature sensitivity and other improved characteristics as compared to quantum well (QW) devices. They have not, however, reached their theoretically predicted 'ideal' characteristics [1, 2]. This is due to inhomogeneous broadening of spectra caused by the size distribution of dots within a population and the presence of a wetting layer. The large density of states present in the wetting layer acts as a carrier reservoir restricting the population of the lower energy dot states [3]. A proposed solution to these problems is to use a tunnelling injection structure, whereby the charge carriers are introduced into the lower dot states by tunnelling from an adjacent injector QW [4, 5]. Under ideal operation, the injected carriers bypass the wetting layer and higher energy dot states. The tunnelling injection structure has previously been used to reduce 'hot carrier' effects in QW structures [6] and used in QD structures with an operating wavelength of 1.1 $\mu$m [7]. In these structures, carriers undergo phonon-assisted injection into the lasing state. Previous studies of carrier dynamics in these tunnel injection InGaAs/GaAs QD lasers [7] have demonstrated significant improvements in performance, including increased small signal modulation bandwidth and reduced temperature dependence of the threshold current. There have, however, been few studies of the fundamental operating mechanisms.

## 2. Experiment

In this paper we address this issue using a relatively new approach to obtain information related to the carrier distribution within a five-layer tunnelling injection QD structure with an operating wavelength of 1.24 $\mu$m. We make use of the segmented contact method [8] to produce modal gain, spontaneous emission and carrier population inversion spectra at temperatures of 300 K and 350 K.

The carrier population inversion ($P_f$) spectra are produced from the ratio of the gain and spontaneous emission spectra as a function of photon energy ($E = h\nu$). The value of $P_f$ over a particular energy range reflects the degree of inversion of a state over that range [8]:

$$P_f(E_{h\nu} = E_1 - E_2) = \frac{f_1(E_1) - f_2(E_2)}{f_1(E_1)\{1 - f_2(E_2)\}}, \qquad (1)$$

where $f_1$ and $f_2$ are the occupation probabilities of the upper and lower states respectively, $P_f$ equals unity when the state

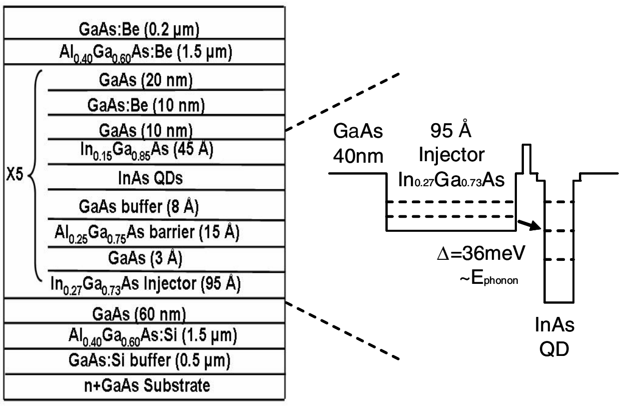


**Figure 1.** Tunnel injection quantum-dot laser heterostructure and schematic band diagram of one period of injector well and dot layer.

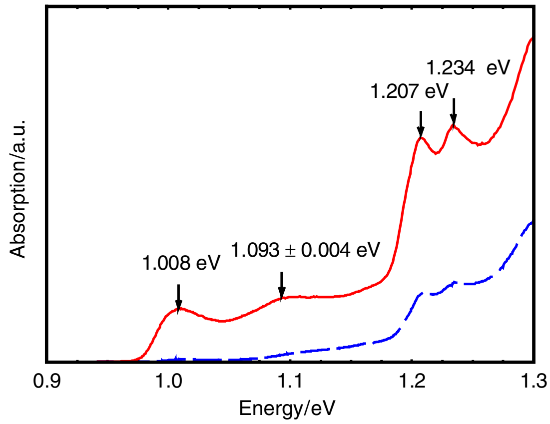


**Figure 2.** Photo-voltage absorption spectra for both TE (solid line) and TM (dashed line) polarizations.

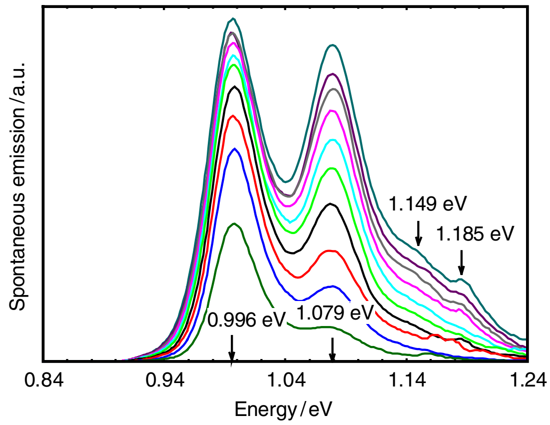


**Figure 3.** Spontaneous emission spectra at 300 K at injection current densities between 111 and 1111 A cm$^{-2}$.

is fully inverted, i.e. when $f_1 = 1$ or $f_2 = 0$. However, no assumptions have to be made as to the nature of the distribution of carriers among the available energy states [8]. If all the carriers are distributed according to Fermi–Dirac statistics (thermally distributed) and described by the same quasi-Fermi level separation $\Delta E_f$, then $P_f$ at particular temperature $T$ can be described by [9]

$$P_f(E_{hv}) = 1 - \exp\left(\frac{E_{hv} - \Delta E_f}{K_B T}\right). \qquad (2)$$

This function will be compared to the experimentally determined carrier distribution spectra to test whether the carriers are distributed according to the Fermi–Dirac statistics. Where the experimental data do not agree with the calculated curves, we conclude that the states present in the system are not in thermal equilibrium. We have previously tested a large number of QW and QD dot structures in this manner and have found that at room temperature and above the carriers are almost always in quasi-equilibrium [9–11], although one exception to this has been observed where the ground state and excited state were observed to be separate in quasi-equilibrium at 300 K with the ground state being relatively underpopulated (characterized by a smaller quasi-Fermi level separation) [12].

The device heterostructure used in this work, as shown in figure 1, was grown by molecular beam epitaxy on a (0 0 1) GaAs substrate. It consists of five repeat InAs QD layers, each with a coupled $In_{0.27}Ga_{0.73}As$ injector well separated by an $Al_{0.25}Ga_{0.75}As$ barrier. The ground state of the injector well is separated from the dot first excited state by the energy of a phonon of approximately 36 meV, and the carriers are injected into this state before relaxing to the lasing state. Further details of the design and growth can be found in [13] and references therein.

## 3. Results

### *3.1. Photo-voltage spectroscopy*

The various energy transitions which are present in the structure and their separation have been measured using polarization-sensitive photo-voltage spectroscopy [14] at room temperature. The measured data are shown in figure 2. The TE polarization spectrum (solid line) shows the inhomogeneously broadened dot ground and first excited state transition peaks separated by ~85 meV together with two sharp peaks at higher energy, which we attribute to transitions in the injector well. Higher energy dot transitions cannot be resolved in this spectrum due to the close proximity of the injector well, but their presence makes the peak energy of the first excited transition difficult to identify. For measurements taken with TM polarization (dashed line), absorption due to the injector well is still present but there is no significant absorption from the dot states.

### *3.2. Carrier distribution at 300 K*

The spontaneous emission spectra at 300 K are shown in figure 3. The peak separation between the dot ground and first excited states is 83 meV; this corresponds to peaks seen in the absorption spectrum (figure 2) but in these spectra we can also resolve recombination from the dot second excited state. We note that electrons tunnel from the injector well into the excited electron state of the quantum dots, which is one phonon energy below the well electron energy, and that these values are related to the measured transition energies of figures 2 and 3 through the conduction band offset between the well and dots. We also note that the peak energies of the spontaneous emission do not change with the carrier injection level.

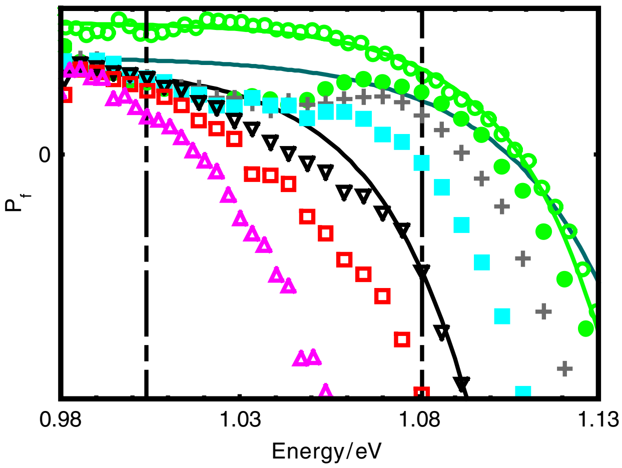


**Figure 4.** Carrier distribution spectra at 300 K at injection current densities between 222 and 1111 A cm$^{-2}$. The data points are the measured data, the solid lines are calculated for a thermal carrier distribution at the quasi-Fermi level separation determined by the transparency point of the gain spectra fitted over a region of the dot first excited state. The carrier distribution spectrum from standard QD sample (open circles) is shown shifted up for clarity.

The $P_f$ spectra at 300 K over the energy range corresponding to the inhomogeneously broadened dot ground and first excited states are illustrated in figure 4. The peak energies of the ground and first excited states extracted from the spontaneous emission are illustrated by dashed lines. In addition, in figure 4, we plot a $P_f$ spectrum at 300 K that represents the typical behaviour seen in 1.3 $\mu$m QD lasers (offset upwards from the other curves for clarity). For this laser, which is a standard five-layer DWELL structure as described in [15], the experimental points are well described by the calculated curve over the whole energy range indicating that the carriers in this sample can be described by quasi-Fermi–Dirac statistics.

The experimental data points for the tunnelling injection structure for a range of current density do not agree with calculated curves over the entire energy range of the system. In this situation, we can fit a curve to a particular region of the experimental data (here we have used the energy range corresponding to a subset of the inhomogeneously broadened dot first excited states) and compare the degree of inversion (value of $P_f$) in that region to other energy ranges within the system.

The experimental data points are similar to the calculated line over the energy ranges near the peak energies of the ground and first excited states. This suggests that over a certain energy range, the ground state has a degree of inversion equivalent to that it would have if it were in thermal equilibrium with the dot first excited state. There is a dip in the experimental data between these two regions of high $P_f$. We conclude that over this energy range, the system is underpopulated.

The energy separation between the regions of high $P_f$ is (80 $\pm$ 10) meV and corresponds to the separation between the ground and excited states, as deduced from the measured spontaneous emission data (figure 3). The amplitude of the dip increases as the level of carrier injection is increased. We believe that this, along with the fact that the spontaneous emission peak energy does not change with increasing current

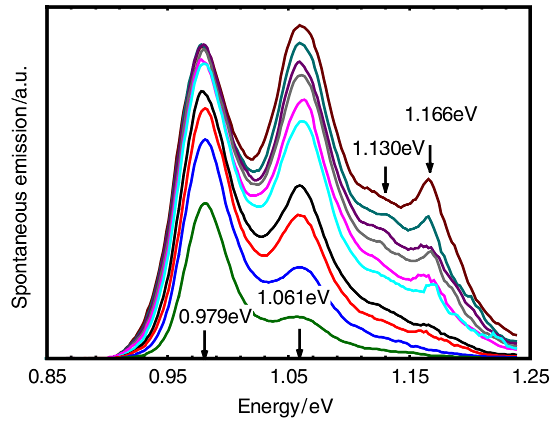


**Figure 5.** Spontaneous emission spectra at 350 K at injection current densities between 111 and 1333 A cm$^{-2}$.

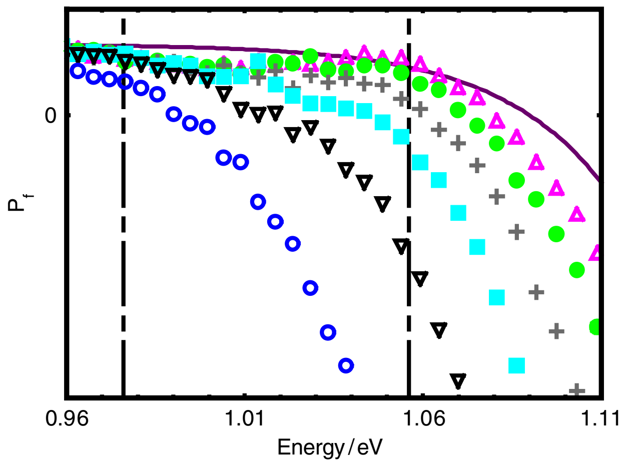


**Figure 6.** Carrier distribution spectra at 350 K at injection current densities between 222 and 1333 A cm$^{-2}$. The data points are the measured data, the solid lines are calculated for a thermal carrier distribution at the quasi-Fermi level separation determined by the transparency point of the gain spectra fitted over a region of the dot first excited state.

density, suggests that the injection process couples carriers into a subset of dots of a specific size and that carriers are able to move between excited and ground states of individual dots in this subset but that dots with a different size are underpopulated. This supports predictions [4] that tunnel injection inherently leads to an effective narrowing of the inhomogeneous linewidth by selective injection into the QDs of the 'right' size.

### *3.3. Carrier distribution at 350 K*

The spontaneous emission spectra at 350 K are illustrated in figure 5. We can see that the first excited state is more prominent than at 300 K. There is also significant recombination from the injector well illustrated by the sharp peak at 1.166 eV. At 300 K this is not the case presumably because at higher temperatures, tunnelling from the well is more difficult with less empty states within the dot for carriers to tunnel into. This leads to a build-up of carriers in the injector well, and hence an increase in recombination from it.

The $P_f$ spectra at 350 K are illustrated in figure 6. As seen in the 300 K data, the region around the excited state peak of the spontaneous emission appears to be more highly populated than states at lower energies would be if the carriers were distributed according to the Fermi–Dirac statistics. However, the dip in $P_f$ between the subset of excited and ground states is less pronounced. This is presumably because at 350 K, the thermal redistribution process is more efficient.

## 4. Conclusion

In summary we have shown that the tunnelling injection structure injects electrons into a subset of the lower energy dot states, where the injector well controls the operation of the device. The carrier distribution spectra contain features which suggest that dots of a particular size within the ensemble are preferentially populated, leading to a reduced spectral broadening of the emission.

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